Chapter 4

THE INDUSTRIAL SECTOR

4.1 INTRODUCTION

This chapter presents an assessment of the possible contribution that an invigorated effort to move energy-efficient technologies that are commercially available, or near commercialization, into the market could make to reducing greenhouse gas emissions from the US. industrial sector by 2010. We begin with some background information on our approach to the assessment and how that approach is shaped by the complexities of the U.S. industrial sector and the available analytical tools for this sector. We then describe the results of our model-based scenario analysis for the year 2010. In subsequent sections we provide examples of the types of technologies that need to come into widespread use to achieve the scenario results. Widespread adoption of these technologies requires appropriate policies (e.g., accelerated research and development (R&D), fiscal incentives, and market conditions). Finally, we describe qualitatively, and illustrate with examples, the role of R&D in providing a steady stream of advanced technologies that can continue to reduce industrial energy intensity and greenhouse gas emissions, into the foreseeable future. Details of the models used in the analysis and the technologies described in this chapter are provided in appendices.

4.1.1 Approach

The industrial sector is extraordinarily complex and heterogeneous. By definition, it includes all manufacturing, as well as agriculture, mining, and construction activities. The manufacturing industries range from those that transform raw materials into more refined forms (e.g., the primary metals and petroleum refining industries) to those that produce highly finished products (e.g., the food processing, pharmaceuticals, and electronics industries). Hundreds of different processes are used to produce thousands of different products. The U.S. chemical industry alone produces more than 70,000 different products at over 12,000 plants. Even within a manufacturing industry, individual firms vary greatly in the outputs they produce and how they produce them. Further, two plants producing identical outputs can use different processes, and two plants using identical processes can use different vintages and types of equipment. In some industries, plants employing the same basic processes can produce a different mix of outputs.

This complexity makes it difficult to conduct this assessment in a "bottom-up" fashion.[1] The available time and resources do not allow us to (1) catalog all of the advanced technologies whose use might be increased under an invigorated effort to move them into the market, (2) identify all the processes in which these technologies might be used, (3) estimate the fraction of the plants that are not already using these technologies, and (4) determine which of these plants would be likely to choose to invest in them under the invigorated effort noted above. Instead, we rely on publicly-available computer-based models to develop rough estimates of the potential for increased investment in energy efficiency more generally, and then supplement these estimates with examples of technologies, the adoption of which would achieve the model results under an invigorated effort to move them into the market.

4.1.1.1 Scenario Analysis

For the scenario portion of the analysis, the ideal analytical tool would be an industrial model that is publicly-available, complete and up-to-date, and has a stock-adjustment mechanism as well as detailed, technology-specific conservation supply curves for all important industrial processes that are affected by energy prices, capital recovery rates, and other economic parameters. We would also like to be able to relate the modeling results to those reported in the US. Department of Energy's *Annual Energy Outlook 1997* (AEO97), which is prepared by the Energy Information Administration using the National Energy Modeling System (NEMS) (EIA 1997b).

No existing modeling tool has all of these features. Instead, we employ two modeling tools that, when used together, provide us with the features we need: (1) the Long-Term Industrial Energy Forecasting (LIEF) model, which provides a mechanism for evaluating general investment in conservation technology as a function of energy prices, capital recovery rates, and other parameters, and (2) the NEMS Industrial Module (NEMS-IM), which captures the effects on energy intensity of groups of specific technologies, but does not model investment in these technologies as functions of energy prices or any other factors. (See Appendix D-1 for a description of these two models and the industry disaggregation scheme used in each.)

We used these two models to develop three scenarios: a "business-as-usual" (BAU) case, an "efficiency" (EFF) case, and a "high-efficiency/low-carbon" (HE/LC) case. These cases are defined, and their results described, in Section 4.2. Our general approach was to use the AEO97 reference case (developed using the NEMS model) as our BAU case. Using the macroeconomic and energy price assumptions in the AEO97 reference case, we adjusted the LIEF model's base case slightly to more closely approximate the overall energy forecast in the AEO97.[2] We then ran the adjusted LIEF model to obtain an efficiency and high-efficiency/low-carbon case. We computed the difference between the LIEF BAU case and the LIEF efficiency case ("delta one"), and between the LIEF BAU case and the LIEF HE/LC case ("delta two"). We applied the LIEF model “deltas” to the NEMS (AEO97 base) results to compute our final estimates for potential greenhouse gas emissions reductions. We also used the NEMS model to explore the extent to which capital stock turnover and technology performance would have to increase to correspond to "delta one" and "delta two."

4.1.1.2 Technology Examples

The technology discussion focuses on energy-conserving technologies that, as a result of past R&D, are currently available for purchase in the market or are highly likely to enter the market within the next few years. While these technologies are available, they have not necessarily been widely adopted and, under current circumstances, may not be – thus the need for an accelerated effort to encourage their adoption and achieve the savings that the models suggest are possible. While there are many reasons for an invigorated effort to adopt these technologies, some of which we discuss later, we temper our expectations to be sensitive to the slow turnover of heavy equipment in industry.[3] Another timing issue is that some energy-intensive industries also have “windows of opportunity” during the next few decades where aging capital equipment must be replaced for environmental or competitive reasons.

We focus on seven energy-intensive industries that are either modeled in detail by the NEMS and LIEF models or are the focus of the DOE Office of Industrial Technologies' (OIT) Industries of the Future process, sometimes referred to as “Vision Industries”: forest products,[4] glass, iron and steel, metal casting, aluminum, chemicals, and petroleum refining. These major energy-using sectors account for about 80% of manufacturing energy use (see Figure 4.1). We also look at cross-cutting technologies (such as energy-efficient motors) that affect all industries. These energy-intensive industries are briefly described in the box below.

Energy-Intensive Industries

Industries are characterized using data collected by the Bureau of the Census from establishments (plants) that are classified in a particular industry based on the value of the production of the plant and the industry that is identified as the origin of that product. This classification system, known as the Standard Industrial Classification (SIC), is being superceded this year by the North American Industry Classification System (NAICS). In addition to economic information collected by the Census, energy consumption is collected for the Energy Information Administration in the Manufacturing Energy Consumption Survey (MECS).

According to the 1994 MECS, the most energy-intensive industries were, in descending order, Petroleum and Coal Products (NAICS 324); Paper and Allied Products (321); Chemicals and Allied Products (325); Primary Metals (331); and Stone, Clay and Glass Products (327). The range of intensity of these industries is from 44.3 to 13.3 thousand Btu per dollar of output (TBtu/$). A brief description of these five most energy-intensive industries follows.

Petroleum and Coal Products. The major activity in this industry is converting crude petroleum into the petroleum products widely used in our economy – gasoline, diesel, fuel oil and lubricants. The process is a complex one of first separating the crude into different products, then recombining these components into the desired products. The separation is done through distillation and cracking that requires high temperatures and pressures, and is affected by the density of the original crude. Environmental considerations have greatly increased the complexity of this process, as reformulated and oxygenated fuels are increasingly needed to assure clean air quality. Another factor that has made for increased energy use in this industry is the declining availability of light crude and the greater processing requirements for heavy crude. Petroleum refining is the most energy-intensive industry with an intensity of 44.3 TBtu/$.

Paper and Allied Products. This industry converts fiber, usually from wood, into paper, pulp or paperboard, and then into a variety of products. The process begins with wood, which is first debarked and chipped, then either mechanically or chemically reduced to a slurry that is bleached, then formed into pulp, paper, or board. Though paper making is a very energy-intensive process, much of the energy used is derived from the biomass that is the basic feed stock for the process. The Forest Products Vision process combines this industry with wood products manufacturing, which includes saw mills, plywood mills and engineered wood products. In 1994, energy intensity was 18.5 TBtu/$.

Chemical and Allied Products. The major segments of this industry are basic chemicals; resins, synthetic rubber and manmade fibers; pesticides, fertilizer and other agricultural chemicals; pharmaceuticals and medicines; paints, coatings, sealants and adhesives; soap, cleaning compounds and toilet preparations; and other chemical products. Basic chemical production includes petrochemicals, industrial gases, and other inorganic chemicals, and other organic chemical manufacture. Basic chemical production uses the bulk of the energy required by this industry and creates the largest volume of products. In all of chemical manufacturing, heat and pressure are used to separate and combine chemical building blocks into saleable products, either for final consumers or to other manufacturing. In 1994, energy intensity was 16.0 TBtu/$. When only basic chemicals are considered, the intensity is about twice as high.

Primary Metals. This industry includes the production of iron and steel (a Vision industry), aluminum (another Vision industry), and a variety of non-ferrous metals – lead, copper and zinc are the most important. The production of iron and steel falls into three sub-industries. *Integrated producers* transform iron ore into pig iron, then convert this to steel. The refined steel is cast or rolled into primary products such as sheet, bars, and billets. *Specialty steel producers* convert pig iron or steel into special products such as stainless and other alloy steels. *Mini-mills* produce primary steel products from scrap steel, usually in an electric arc furnace. Aluminum producers convert alumina (aluminum oxide) into aluminum metal using an electrolytic process. The major producers also convert ore, usually bauxite, into alumina, but that operation falls within the chemical industry classification. The intensity of this industry in 1994 was 15.3 TBtu/$.

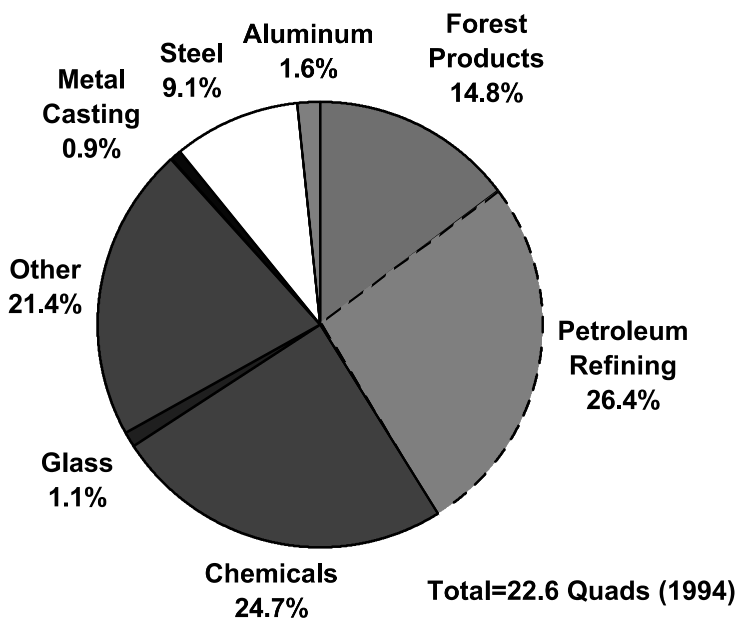
Stone, Clay and Glass Products. “Nonmetallic Mineral Products,” under NAICS, includes cement, glass (a Vision Industry), bricks, lime, and other stone and ceramic products. Pyroprocessing, or the application of heat to assure a chemical reaction, is required in most of these subindustries, which is what makes them so energy-intensive. Cement and lime are formed at high temperatures in a kiln; glass is produced by melting silica sand; bricks, china and pottery are just clay until fired. The intensity of this industry is 13.3 TBtu/$.

4.1.1.3 A Continuing Stream of New Technologies

We assess qualitatively, again through the use of illustrative examples, the contributions that R&D might also make to reducing greenhouse gas emissions over a longer time frame. We describe R&D efforts that can lead to advanced technology offering energy-intensity and greenhouse gas emissions reductions beyond those described in the efficiency and high-efficiency/low-carbon cases, accompanied by rough quantitative estimates where possible. In this portion of the discussion, we again focus on the energy-intensive industries and on cross-cutting technologies. Input for the R&D assessment was sought from technology experts, particularly the OIT Industry of the Future teams and their industry and laboratory partners.

It is worthwhile to think of these more advanced technologies as the source of future emissions reductions *if* the pipeline of R&D is kept full and productive over the entire time horizon. Technology that is currently available to contribute to reduced energy use and emissions exists because R&D in the past is now paying benefits in the form of new technology. If there are to be future benefits, this pipeline must remain full. R&D focusing on efficiency improvements and carbon emissions reductions is needed to generate the new technologies of the future.

Figure 4.1 Share of Energy-Intensive Industries in Manufacturing End-Use Energy: 1994



4.2 ENERGY EFFICIENCY EMISSIONS REDUCTIONS

The LIEF model contains conservation supply curves for various industries that correlate energy conservation investment as a function of energy prices. These curves have been calibrated to historical industry data using an implicit Capital Recovery Factor (CRF) of 33%. CRFs and associated discount rates at this level or higher – representing a requirement that these investments pay back the capital outlay within a few years – have been found to characterize much of the decision-making in industry on investments in energy-efficiency technologies and on similar investments. At the same time, firms have another class of investment decisions – termed "strategic" investments – that are characterized by a lower CRF or discount rate (i.e., the initial investments are allowed to pay back over a longer period) (see Ross 1990). One way, then, to simulate an increased investment in energy-efficient technology is to postulate a policy or set of policies that would lead industry to apply something like this more "strategic" discount rate to energy-efficiency investments. This effect could be induced via policies that served to decrease the first cost of such investments or that resulted in increased annual cost savings.

Another way to simulate such an increase in technology investment is to directly increase the factor that represents the penetration rate of new technologies. The penetration rate parameter in LIEF provides a measure of the rate at which industry adopts conservation projects. Firms do not immediately adopt all technologies that meet their criteria for cost-effectiveness and other factors – delays may represent a lack of capital, other priorities for the use of available capital funds, scheduling concerns, or simply a lack of awareness of the technologies. The box to the right discusses some of the factors that may affect the adoption of new, more energy-efficient technologies and policies that could be used to influence them. An increase in this penetration rate reflects a higher priority placed on energy conservation by industry as well as better information dissemination (Ross et al. 1993).

We have used both of these factors to simulate the efficiency case and the high-efficiency/low-carbon case for the industrial sector. We assume that either the discount rate or the penetration rate is affected in the efficiency case, and that both may be affected in the high-efficiency/low-carbon case. Further details on how the models were used to simulate these cases are provided in Appendix D-1.

Increasing the Use of Advanced, Energy-Efficient Technology in Industry

Many aspects of business decision-making may slow the adoption of energy-efficient technology. They include :

- ***High capital intensity of process industry leading to slow capital stock turnover,***
- ***Perceived riskiness of new technology,***
- ***Lack of internal funding resulting in less capital for energy projects,***
- ***Lack of information.***

Policies that might reduce these effects are*:*

- ***Accelerated depreciation,***
- ***Better demonstration and showcase efforts to prove technology reliability,***
- ***Reducing first costs and/or achieving better performance through aggressive R&D,***
- ***Rebates or tax credits,***
- ***Information programs and energy management services,***
- ***Regulation and efficiency standards,***
- ***Pricing and fiscal policies,***
- ***Other economic incentive programs,***
- ***The exemplary role of governments.***

These policies can be interpreted as changing the effective or perceived hurdle rates for efficiency investments or increasing the old capital turnover and adoption rates for new technology.

4.2.1 Business-as-Usual Case

Our business-as-usual (BAU) case is the AEO97 reference case. Under this case, national economic output, measured by gross domestic product (GDP) is projected to increase by 1.9% annually to the year 2010. Within this overall growth, the manufacturing sector growth rate is projected at 2.1% per year, with energy-intensive industries growing at half the rate of non-energy-intensive industries, 1.3 versus 2.6%. The leading growth sectors within manufacturing are projected to be industrial machinery, electronic equipment, and transportation equipment. Of all the manufacturing subsectors, electronic equipment is expected to have the highest growth rate, twice that of the manufacturing sector as a whole.

Total energy intensity, to the year 2010, is projected to decline by 1.1% per year. Among industry sectors, the largest declines in total energy intensity are projected for the pulp and paper and glass industries, with the cement industry third. Electricity intensity is projected to decline by 0.5% overall but with considerable inter-industry variation. The largest decline, 1.1% in the pulp and paper industry, contrasts with an increase of the same magnitude in the iron and steel industry. The distribution of primary energy consumption among end-uses is expected to remain stable, with more than two-thirds of industrial sector use accounted for by manufacturing heat and power requirements and the remaining third split about equally among non-manufacturing heat and power applications and use as process feed-stocks. For manufacturing heat and power, the largest energy-consuming industries are petroleum refining, chemicals, and pulp and paper production. The long-term trend of declining energy intensity in manufacturing is expected to continue, representing an 18% decline in energy intensity between 1995 and 2010. This trend is due to both adoption of energy-efficient technologies *and* relatively lower growth rates in the more energy-intensive industries. The effects of industry mix shifting toward less energy-intensive industries is stronger than the efficient-technology effect on the overall rate of change in energy intensity.

The AEO97 reference case assumes that there are no changes in federal energy or environmental policies over the forecast period. To the extent that the NEMS model reflects recent historical trends in industrial technology R&D performance, availability, and introduction, current and future private and government R&D funding for new and emerging technologies consistent with recent history contributes to the reference case decline in energy intensity.

4.2.2 Efficiency and High-Efficiency/Low-Carbon Cases

The industrial sector forecasts for the efficiency and high-efficiency/low-carbon (HE/LC) cases use the AEO97 energy prices and macroeconomic activity forecasts as a starting point. We assume no changes in economic activity that might arise from changes in energy markets.[5] Moreover, we assume no changes in the energy prices that could occur under conditions of lower energy demand. Energy markets adjust to changes in demand. This means that reduced demand in the EFF and HE/LC cases would lead to lower energy prices, thereby reducing incentives for efficiency gains.

The efficiency case assumes that industrial firms apply a "strategic" discount rate (or hurdle rate) to energy-savings investments. We simulate this effect in LIEF by changing the Capital Recovery Factor (CRF) from 33% to 15% to reflect the lower hurdle rate. Not all cost-effective technologies are assumed to instantaneously penetrate the market. The HE/LC case is based on the assumption that the penetration rate of the technologies that are cost-effective under a CRF of 15% doubles on average.[6] The LIEF model penetration factor was set initially at 3%, roughly calibrated to the NEMS BAU. The NEMS model uses rates of capital stock turnover that are similar in magnitude. This implies that, in the high-efficiency/low-carbon scenario, some acceleration of stock turnover is expected. This could occur under policy incentives for early retirement or economic incentives attributable to the costs and performance of new process technology that would make old equipment economically obsolete earlier than has been the case historically.

Table 4.1 summarizes the results in the energy consumption levels forecast by the AEO97. The overall change in energy use between 1997 and 2010 is shown for the BAU case in the first two columns for fossil fuels and electricity use (including system conversion losses). Renewables, feedstocks and non-energy uses of petroleum (e.g. asphalt, waxes, lubricants, etc.) are also shown, but are unaffected by the LIEF analysis. The next two columns show the effects of the efficiency case and the HE/LC case, as forecast by LIEF, on the AEO97 BAU case. Figure 4.2 shows that the HE/LC case approaches zero growth with energy use increasing by only 1.4 quads (4%) between 1997 and 2010, in spite of an output increase of 30% over the period.

Table 4.1 Industrial Energy Use: AEO97 Business-as-Usual Case, and Efficiency and High-Efficiency/Low-Carbon Forecasts by LIEF (Quads)

	AEO97		LIEF	
		BAU	Efficiency Case	HE/LC Case
	1997	2010	2010	2010
Electricity (incl. related losses)	11.3	13.2	12.2 (7.6%)	11.2 (15.2%)
Fossil Fuels	16.0	18.2	17.2 (5.4%)	16.3 (10.4%)
Subtotal	27.3	31.4	29.4 (6.5%)	27.5 (12.5%)
Renewables*	1.8	2.3	2.3	2.3
Petrochemical Feedstocks and non-energy uses of petroleum	5.3	6.0	6.0	6.0
Total	34.4	39.7	37.6	35.8

Note: Numbers in parentheses represent the percent reduction compared to 2010 BAU case.

* Expanded renewable use is considered in Section 4.3.

Figure 4.2 BAU Energy Use and Projected Efficiency Cases in 2010 (quads)*

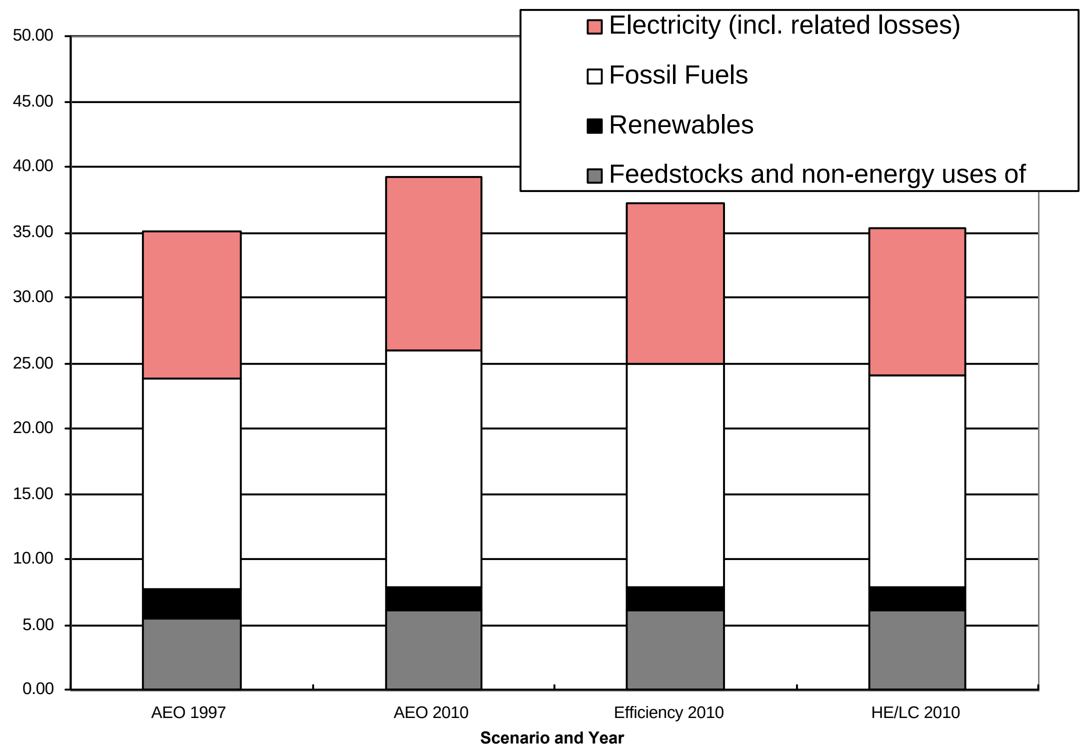


Table 4.2 shows the results of these analyses for ten major economic sectors of U.S. industry.[7] The results in Table 4.2 are expressed in terms of an additional annual percentage reduction in sectoral energy intensity compared with the BAU case. The efficiency case reduces total energy intensity growth by an additional 0.5% per year. The HE/LC case reduces the growth in energy intensity by over 1% per year, relative to the BAU case, and reduces the growth in electricity use by more than 1% annually (1.3%).

Table 4.2 LIEF Results: Change in Energy Intensity, Annual Average Rate, 1997-2010, Compared with the Business-as-Usual Case (% change)**

	Efficiency Case CRF = 15% Penetration = Normal			HE/LC Case CRF = 15% Penetration = Double		
	Electric	Fuels	Total	Electric	Fuels	Total
Heavy Manufacturing	-0.36%	-0.28%	-0.31%	-0.70%	-0.60%	-0.63%
Pulp & Paper	-0.35%	-0.28%	-0.31%	-0.72%	-0.60%	-0.64%
Bulk Chemicals	-0.40%	-0.28%	-0.33%	-0.81%	-0.60%	-0.69%
Petroleum	-0.47%	-0.28%	-0.31%	-0.78%	-0.60%	-0.63%
Glass	-0.39%	-0.29%	-0.34%	-0.71%	-0.56%	-0.63%
Cement	-0.28%	-0.27%	-0.27%	-0.65%	-0.65%	-0.65%
Iron & Steel	-0.43%	-0.29%	-0.34%	-0.78%	-0.56%	-0.64%
Aluminum	-0.15%	-0.29%	-0.16%	-0.30%	-0.56%	-0.31%
Other	-0.35%	-0.28%	-0.31%	-0.75%	-0.63%	-0.69%
Light Manufacturing	-0.86%	-0.61%	-0.78%	-1.76%	-1.16%	-1.56%
Non-Manufacturing*	-0.67%	-0.67%	-0.67%	-1.26%	-01.27%	-1.27%
All Industry	-0.64%	-0.43%	-0.52%	-1.28%	-0.84%	-1.04%

*Non-manufacturing includes agriculture, construction, and mining (including energy extractions).

** Excludes renewables, feedstocks and non-energy uses of petroleum.

Table 4.3 translates these changes in energy intensity into percentage changes (reduction) in energy consumption in 2010, relative to the BAU case. In the HE/LC case, overall energy consumption decreases by more that 12% in 2010 relative to the BAU case, while the decrease in the Efficiency case is more than 6%. The results for individual industries vary; the declines in energy intensive industries are close to the average for all of industry, but non-energy intensive sectors show percentage declines of about twice that of heavy industry.

That the percentage reduction in energy use is higher in light industry stems from two reasons. The first is that energy is a very small part of the costs in these sectors so that energy efficiency investment is often overlooked. The LIEF model represents this by a large difference between the average light manufacturing plants and the most efficient ones. The high growth sectors in light manufacturing have relatively larger opportunities to make significant percentage reductions than do their energy intensive counterparts, who have already done so in response to rising energy prices in the 1970s. In addition, light industries' energy use is dominated by electricity. Electricity savings in light manufacturing comes largely from computer controls, motor systems, as well as contributions from lighting and HVAC that are similar to technologies discussed in the buildings chapter

The second is that the growth in output for light industry is much higher than for heavy industry. Output grows more than 80% by the year 2010 for light industry, but only 30% for heavy industry. As a result, in the BAU case, electricity demand nearly doubles for light industry and fossil fuel use grows more than 60%. Fossil fuel demand for heavy industry only increased by 12% in the BAU case, while electricity demand increases by 48%.

The difference between light and heavy manufacturing is a major source of the difference in the energy savings (on a percentage basis) between fossil fuels and electric energy. One should note that, while these percentage savings vary, a significant portion of the energy savings in absolute terms still come from fossil fuel use reduction in heavy industry, e.g. fossil fuel reductions in heavy manufacturing is about 8% while the industry total for fossil fuels is about 12%.

Table 4.3 LIEF Results: Energy Savings in the Year 2010 Compared with the Business-as-Usual Case (% reduction)**

	Efficiency Case CRF = 15% Penetration = Normal			HE/LC Case CRF = 15% Penetration = Double		
	Electric*	Fuels	Total*	Electric*	Fuels	Total*
Heavy Manufacturing	4.6%	3.6%	4.0%	8.7%	7.5%	7.9%
Pulp & Paper	4.5%	3.6%	3.9%	9.0%	7.5%	8.0%
Bulk Chemicals	5.0%	3.6%	4.2%	9.9%	7.5%	8.5%
Petroleum	5.9%	3.6%	3.9%	9.7%	7.5%	7.8%
Glass	5.0%	3.7%	4.3%	8.8%	7.0%	7.8%
Cement	3.5%	3.5%	3.5%	8.2%	8.1%	8.1%
Iron & Steel	5.5%	3.7%	4.4%	9.6%	7.0%	8.0%
Aluminum	2.0%	3.7%	2.0%	3.8%	7.0%	4.0%
Other	4.4%	3.5%	3.9%	9.3%	7.9%	8.5%
Light Manufacturing	10.6%	7.6%	9.6%	20.4%	14.0%	18.3%
Non-Manufacturing*	8.3%	8.3%	8.3%	15.1%	15.2%	15.2%
All Industry	8.0%	5.4%	6.6%	15.30%	10.4%	12.5%

These numbers are based on electricity system-average energy loss from the business-as-usual case.

*Non-manufacturing includes agriculture, construction, and mining (including energy extraction).

** Excludes renewables, feedstocks and non-energy uses of petroleum.

Table 4.4 illustrates how the energy use by fuel type is affected in each scenario. Natural gas use, the dominant fuel use by industry, declines the most in absolute terms. Petrochemical feed stocks, other non-energy uses of petroleum, and renewables are assumed to be unaffected in the efficiency and high-efficiency/low-carbon cases and do not contribute to the carbon emissions.

Table 4.4 Change in Industrial Energy Use by Fuel Type

	AEO		Efficiency	HE/LC
	1997	2010	2010	2010
Natural gas (billion cu ft)	9,914	11,103	10,303	9,564
Coal and coke (1000 short tons)	104,716	113,741	10,551	97,976
Liquid fuels - incl. LPG (1000 bbl)	695,160	697,300	647,090	600,648
Petrochemical feed stocks & other petroleum (1000 bbl)	925,536	1,180,979	1,180,979	1,180,979

Table 4.5 provides carbon emissions estimates for 2010 in metric tons. Because LIEF does not model fossil fuel choice, estimates of carbon reductions are based on the fossil fuel mix and emission factors in NEMS. For fossil fuels, there are two ways to compute carbon emissions. The first is to assume that efficiency affects fuel reductions through the average fuel mix. The second is to assume that most energy-efficiency reductions operate on the margin (i.e., they affect those fuels that constitute the growth in the BAU forecast).

Table 4.5 Carbon Emissions Estimates (MtC per year)

	AEO97		Efficiency Case	HE/LC Case
	1997	2010	2010	2010
Electricity	172	213	204 (4.5%)	186 (12.7%) *
Fossil Fuels	311	335	317 (5.4%)	300 (10.4%)
Industry Total	482	548	521 (5.1%)	486 (11.3%)

*A portion of the reduction in carbon emissions associated with the high-efficiency/low-carbon case is due to changes in the electricity generation mix prompted by the charge of $50/tonne of carbon (see Chapter 6). Numbers in parentheses represent the percent reduction compared to 2010 BAU case.

An examination of the change in fossil fuel mix in industry in the AEO97 found that no fuel's share changed by more than 1%. Consequently, using the average industrial fossil fuel mix from the AEO97 is a reasonable approach to compute the change in greenhouse gas emissions. However, the electric utility industry shows an increasing share of natural gas. Therefore the carbon reductions for electricity use in Table 4.5 are based on the marginal carbon emission rates, rather than the average (see Chapter 6 for more details).

These overall carbon reductions are translated into industry-specific carbon reductions in Table 4.6. Heavy manufacturing contributes about one-third of the savings in both the efficiency and HE/LC cases. The large contribution of carbon savings from light industry comes mostly from electricity efficiency. Electricity use in this sector is growing rapidly – almost doubling – in the BAU case.

Table 4.6 Industry-Specific Reductions in Carbon Emissions (MtC per year in 2010)

	Efficiency			HE/LC		
	Electric	Fuels	Total	Electric	Fuels	Total
Heavy Manufacturing	2.1	7.1	9.2	5.9	14.8	20.6
Pulp & Paper	0.3	1.1	1.5	1.0	2.3	3.3
Bulk Chemicals	0.7	1.5	2.2	1.9	3.2	5.1
Petroleum	0.3	2.5	2.7	0.6	5.2	5.8
Glass	0.1	0.2	0.2	0.2	0.3	0.5
Cement	0.0	0.2	0.3	0.1	0.5	0.6
Iron & Steel	0.4	1.2	1.6	1.1	2.3	3.4
Aluminum	0.1	0.0	0.2	0.4	0.0	0.4
Other	0.2	0.4	0.6	0.6	0.9	1.5
Light Manufacturing	6.3	5.2	11.5	17.8	9.7	27.4
Non-Manufacturing*	1.3	5.7	7.0	3.4	10.4	13.8
Total	9.6	18.1	27.7	27.0	34.9	61.9

* Non-manufacturing includes agriculture, construction, and mining (including energy extraction).

4.2.3 Comparison with the NEMS model

The NEMS model provides a different approach and perspective on the EFF and HE/LC cases. The NEMS model uses a stock turnover approach to project the change in energy use. New technology is projected to be more efficient; thus, as capital is replaced, the overall energy requirements in the industry decline. To compare the scenarios, the NEMS industrial model was run under alternative assumptions and compared to those corresponding industry sectors in LIEF (see Table 4.7).

When the retirement rate of capital is doubled in the NEMS industrial model, the decline in total energy use ranges from 1-8%, depending on the sector. On the other hand, when the performance of new technology is assumed to double (i.e., the relative energy intensities of new technologies in NEMS decline twice as fast as in the BAU case), even larger reductions in energy use are achieved for all sectors except cement and steel. These parametric variations in the NEMS model illustrate, in rough magnitude, what rate of technology improvement or stock turnover would be consistent with the EFF and HE/LC case. For example, only in the iron and steel industry does the doubling of the retirement rate result in energy savings comparable to those in the HE/LC case; for all other industries, it would require more effort than simply doubling the capital stock turnover to achieve comparable savings. For aluminum and glass, the energy savings resulting from the NEMS run that doubles technology performance are higher than the energy savings in the HE/LC case, suggesting that for these sectors more rapid technology development is an important part of future savings. This is particularly true of the aluminum sector.

Table 4.7 Comparison of Year 2010 Total Energy Savings Relative to BAU in the NEMS and LIEF Models

	LIEF		NEMS	
	Efficiency Case	HE/LC Case	Doubled Retirement	Doubled Technology Performance
Paper	3.9%	8.0%	4.9%	7.5%
Chemicals	4.2%	8.5%	1.3%	5.0%
Glass	4.3%	7.8%	3.6%	9.9%
Cement	3.5%	8.1%	5.7%	3.6%
Iron and Steel	4.4%	8.0%	8.2%	2.9%
Aluminum	2.0%	4.0%	1.2%	7.8%

4.2.4 The Historical Context of Energy Efficiency in Industry

Over time, both the “what” and the “how” of industry output changes. Buggies and whips have disappeared, but automobile production has taken their place. And while the Model T was mass-produced, today's methods of production are only vaguely reminiscent of Henry Ford's assembly line. Energy use in manufacturing and other industry sectors has changed due to both product and process transformation. Energy use changes occur because of energy-efficiency improvements over time as well as changes in the mix of industries. Rough approximation of the importance of these two factors indicates that efficiency accounts for about two-thirds of the change, while the shift in the mix of industries accounts for about one-third. Put into historical perspective, forecasts of energy use and energy intensity changes used for this analysis are modest changes and, we believe, more than just possibilities. With appropriate and effective policy measures to accelerate the adoption of technologies that are currently, or will soon be, available, the efficiency gains and energy and carbon savings projected could easily be achieved.

A study published by DOE (1995) illustrates how rapidly energy intensity in the industrial sector can decline. Between 1972, the last full year prior to the effect of the first oil price shock, and 1985, when energy prices fell, the rate of decline in energy intensity in industry was 2.74% per year. During the period of the most rapid decline, from 1975 to 1983, industrial sector energy intensity fell by 3.12% per year. These numbers show that, when industry has a major incentive to reduce energy use, it will do so. By the same token, when the incentives are reduced, so are the improvements. Between 1984 and 1991, energy intensity in the industrial sector declined by less than 1% per year, and in four of these years, the intensity actually increased.[8] Of the energy savings that occurred in the industrial sector between the mid-1970s and the early 1990s, this report suggests that about one-third of the total was attributable to compositional shifts (i.e., shifts from high energy-intensive industries to industries with lower energy intensity). The remainder was attributable to reductions in energy intensity within industries.

In the BAU forecast, total energy intensity declines at about 1.1% per year, with more than half of this decline (0.6%) attributable to projected composition effects. If one takes the efficiency component of the total energy intensity decline forecast for the BAU case (0.5% per year) and adds the additional 0.85% per year from the high-efficiency/low-carbon case, the HE/LC case has a rate of energy intensity decline (1.35%) that is slightly below the historical rate over the period 1972-1991 (1.89%).

4.2.5 The Costs of Achieving the Efficiency and HE/LC Cases

The LIEF model conservation supply curves can be used to compute the investment implied by the forecast energy reductions. These estimates, shown in Table 4.8, are the additional investment required to achieve the energy savings presented above. Due to the long-lived nature of industrial capital goods, this cumulative investment in more efficient and productive industrial plant and equipment continues to generate energy and costs savings, relative to the base case, after the 2010 time horizon.

LIEF projects that this level of investment is profitable with the BAU forecast energy prices and a CRF of 15%. The energy savings provides about a seven-year payback on the initial investment. The magnitude of the up-front costs, which are paid back only over time, may be an issue in designing policies to spur this enhanced technology penetration.

To put this level of investment in energy efficiency into context, we compare it to total investment in manufacturing. If the cumulative investment in energy efficiency is spread out evenly over the 13-year time period, the HE/LC case would require a $3.6 billion increase in annual investment in efficiency technology. In 1992, total investment in manufacturing (not including agriculture, construction, and mining) was $110.1 billion (1995$). Thus, the incremental annual investment needed to achieve the HE/LC case represents a 3.3% increase over the level of manufacturing investment for 1992.

Table 4.8 Cumulative Incremental Investment (1998-2010) for Energy Efficiency Implied by the LIEF Model to Achieve the Forecast Energy Reductions (billions of 1995$)

	Efficiency Case	HE/LC Case
Fossil Fuels	7.4	15.2
Electricity	15.8	32.0
Total	23.2	47.2

Historical behavior with respect to energy efficiency investments has been characterized by implicit marginal discount rates equivalent to 33% capital recovery. The efficiency case is based on the notion that the marginal return on energy efficiency will be closer (or equal) to a *strategic* discount rate, represented here as a 15% CRF. For example, this translates to a marginal real return of 12.5% per year on a 15-year investment, which we will use for illustrative purposes. It is from this perspective that the efficiency case reflects ‘cost-effective’ investments. The ‘last’ investment will produce cost savings that will provide a return of 12.5%; other investments will generate higher returns. On average, the return will be higher than the marginal, or ‘last’, energy-efficiency project.

Table 4.9 shows the private investment cost of an investment in efficiency in a *single year* , compared to the value of the energy savings that would continue to accrue thereafter. The first line in the table is the incremental investment in the last year of our forecast, 2010. The second and third lines are the change in consumption and expenditure of energy for that year, which are negative since energy consumption is reduced. One can see that investments generate annual savings of about a third of the initial outlay. This is an average return that is quite a bit higher than the assumed marginal return of 12.5%. Recall that the marginal return is the ‘last’ cost-effective investment, which just pays for itself at the 12.5% rate.

Table 4.9 also shows the total energy savings and direct private costs of the scenario. These costs are generated using the cost of conserved energy (CCE) method detailed in Appendix A-1.3. For the efficiency scenario the energy savings exceed the direct private investment costs by $4 billion. The HE/LC scenario has energy savings in excess of direct investment costs of $7 billion.

Table 4.9 Net Costs of Private Investment for Energy Savings in the Efficiency and High-Efficiency/Low-Carbon Cases (millions of 1995$)

		Efficiency		HE/LC	
	Units	Fossil Fuels	Electric (End-use)	Fossil Fuels	Electric (End-use)
Investment in 2010	M$	$800	$1,700	$1,500	$3,200
Annual Energy Reduction	TBtu	94	47	178	82
Annual Reduction in Energy Costs	M$	$300	$600	$600	$1,100
Total Energy Redirection	TBtu	900	336	1800	685
Total Investment Cost	M$	$1,100	$1,800	$2,400	$4,100

Note: Costs are based on the annualized costs over the time period, not the cummulative investments.

We believe that most, if not all, of the difference between the observed behavioral CRF of 33% and the 15% CRF is due largely to factors that preclude firms from using these lower marginal rates for energy-efficiency investments, such as transaction costs, agency costs, the lack of information or the cost of acquiring it, perceived risk, etc. However, policies will be required to remove these factors and shift investment behavior to prioritize energy efficiency the same as other corporate investment. These policies will have a public cost.

The HE/LC case also focuses on 'cost-effective' investment under the same notion of these lowered, strategic, marginal rates of return. However, one important difference in the HE/LC scenario is that a higher adoption rate is assumed. While some additional penetration, relative to the BAU, may be accounted for by further transformation of the market of energy-efficient practices we feel that some accelerated retirement may also take place. When the economic losses of accelerated retirement are accounted for, this implies that, at the margin, all investments are not likely to be cost-effective at our assumed 15% CRF. Since we do not have a model to account for this potential early retirement and the economic losses, we must caveat our estimates of investment. The energy savings from the HE/LC scenario in Table 4.9 does not change, but the investment cost may be understated by the amount of loss due to any early retirement that may occur. Because the net benefit is still greater than the annualized investment we calculate, then unaccounted costs may be about twice our estimated energy-efficiency investment, with the HE/LC scenario remaining 'cost-effective' on average.

A carbon-based fuel price increase was considered and simulated using LIEF for a number of carbon shadow prices. Energy price increases alone do not have a very dramatic effect on energy use in the LIEF model. While they do have some affect on the options to reduce energy use, they have no endogenous affect on the rate of penetration of new technology in the model. For example, a $50 shadow price for carbon increases shifts the "ideal" energy-output ratio by only 8.5% for electricity and 5% for fossil fuel. The gap between the ideal and actual energy-output ratios is a measure of the conservation potential for the sector. Under the BAU case, this gap is 3.8% for electricity and 4% for fossil fuel. Under the EFF case, this gap is 27.6% for electricity and 15.3% for fossil fuels. Under the $50 shadow price case, the gap is 9.5% for electricity and 7% for fossil fuels. To achieve the same ideal energy-output ratio as the HE/LC case would require a shadow price of $250 for fossil fuels and $300 for electricity. Table 4.10 shows the carbon reduction and the percentage reduction in electricity and fossil fuels that result from simulation of different carbon shadow prices.

Table 4.10 Effect of Different Carbon Shadow Price Simulations on Electricity and Fossil Fuel Reductions

Shadow	Electricity		Fossil Fuels	
Price of Carbon	% of BAU	Carbon Saved	% of BAU	Carbon Saved
25	98.4	3	99.0	3
50	97.1	6	98.2	6
100	95.1	10	96.9	10
200	92.2	16	94.8	17
300	90.1	20	93.3	22
400	88.6	23	92.3	26

The HE/LC case reduces electricity to 85.2% of the BAU case and fossil fuel to 92.5%. The energy/carbon savings in the table would be larger if these higher prices systematically affect the penetration rates of new technology, which one would expect. However, penetration rates are currently parametric in LIEF, and since we have very little information about how price changes affect penetration rates, we have not altered that parameter for this exercise. Given the belief that the rise in prices would increase penetration, the estimates of energy and carbon savings from LIEF would represent an upper bound on the required carbon tax or a lower bound on the savings.

The implications of the ‘standalone’ analysis of carbon shadow prices is that a variety of polices well beyond a carbon permit charge would be required to achieve the savings projected in these scenarios.

4.3 ADDITIONAL EMISSIONS REDUCTIONS FROM INDUSTRIAL LOW-CARBON TECHNOLOGIES

4.3.1 Introduction and Summary

Industrial low-carbon technologies reduce greenhouse gas emissions through means other than traditional energy efficiency. We separate low-carbon technologies into three types:

Power-system efficiency maximization (PSEM) technologies: such technology systems comprise mainly existing technologies assembled in an innovative way so as to maximize energy efficiency at certain types of locations for particular industries' heat and power needs.

Fuel-switching technologies: these reduce carbon emissions by using low- or no-carbon fuels instead of high-carbon fuels. Many energy forecasting models, including LIEF and NEMS, incorporate switching from oil, coal or electricity to less carbon-intensive gas. They do not, however, generally incorporate switching to new advanced biomass or other new renewable technologies. Both of these low-carbon technology types are often grouped with energy-efficiency technologies. We separate them from efficiency technologies in this chapter because their additional contributions to carbon reductions are not generally included in traditional energy models.

Low process carbon technologies: this type reduces or avoids the emission of CO_2 and other greenhouse gases from industrial processes, not from combustion. They are clearly not included in energy models. We have found that most of these emissions are non-CO_2 greenhouse gases. Because these emissions do not involve energy, they have not been included in energy-focused carbon analyses. However, as shown in Section 4.3.4, these non-energy emissions account for a third of total greenhouse gas equivalent emissions in the industrial sector. (Industrial CO_2 emissions from energy are projected to be 482 MtC equivalent in 1997 (EIA 1996) and non-energy-related carbon equivalent emissions were 244 MtC equivalent in 1994).

This section provides examples, rather than a comprehensive survey, of low-carbon technologies. Such a survey would have been difficult because, unlike traditional energy-efficiency technologies, these technologies do not have a long history of being analyzed from the perspective of reducing carbon equivalent emissions. However, as shown in Table 4.11, just these examples showed great potential reductions. Thus, a comprehensive survey of these technologies is an important area for future analysis in the industrial sector. Note that the carbon reductions presented are in addition to the carbon savings of Section 4.2.2. Some of these technologies also feature carbon reductions due to traditional energy efficiency. We used the energy-efficiency projections for the various traditional markets presented in Section 4.2.2 to subtract these carbon savings from the technologies' estimated overall carbon reduction. Greenhouse reductions from "low process carbon" technologies are not included in this report's summary tally of carbon reduction potential because of the report's focus on combustion-related emissions.

In the following sections, we provide examples of the three types of low-carbon industrial technologies. The Advanced Turbine System (ATS) described in Section 4.3.2 is an example of a PSEM technology. It is a combined heat and power (CHP) system that replaces grid electricity and steam from industrial boilers with a highly efficient on-site natural gas-fired turbine that generates both electricity and steam. The carbon reductions from on-site CHP were not included in Section 4.2.2. The ATS may also further maximize system efficiency by replacing electricity used to drive motors that drive equipment with direct power for the equipment. Even when used as a power-only technology, ATS reduces carbon emissions because it is located on-site – avoiding transmission and distribution (T&D) losses. The ATS is also a fuel-switching technology if it replaces high-carbon fuels such as coal used in the boilers with natural gas or no-carbon biomass gas.

Section 4.3.3 gives an example of a fuel-switching technology. Black liquor and biomass gasifiers integrated with combustion turbines replace biomass boilers and grid electricity. In the near and medium time frame, biomass and black liquor gasification technologies provide the option of switching from a high-carbon to a “no-carbon” fuel. Note that the advanced technologies described in Section 4.3.3 are also PSEM technologies because they replace inefficient biomass boilers and grid electricity with biomass gasification combined heat and power systems.

Section 4.3.4 describes two low process carbon technologies. The first, the advanced aluminum production cell, shows that for some industrial processes there are multiple opportunities for reducing carbon equivalent emissions. The second involves the substitution of waste products – fly ash and blast furnace slag – for a portion of the calcined cement clinker intermediate product in cement production. Both of the examples reduce carbon through improved energy efficiency in addition to reducing or eliminating carbon equivalent process emissions.

A summary of the carbon reductions from these technologies is given in Table 4.11 for both the efficiency and the high-efficiency/low-carbon (HE/LC) cases.

Table 4.11 Examples of Additional Carbon Equivalent Reductions by 2010 Resulting From Low-Carbon Technologies* (MtC equivalent)

	Efficiency Case	High-Efficiency/Low-Carbon Case
Power System Efficiency Maximization Technology (PSEM)		
Advanced Turbine Systems	5-7	14-24
Fuel-Switching Technology		
Forest Products IGCC	5	10
Low Process Carbon Technologies		
New Aluminum Production Cell	0–1	2–4
Cement Clinker Replacement	-	1–2
Total	**10 13**	**27-40**

*These reductions are not accounted for in Section 4.2.2.

4.3.2 Power System Efficiency Maximization Technologies

Power-system efficiency maximization technologies are grounded in the second law of thermodynamics. PSEM technologies take advantage of the fact that waste heat is always produced. Such systems also reduce or avoid extra energy conversion and process steps that waste energy. The key to PSEM is the system. Instead of using a separate technology for electricity for the company's PCs, building heating and cooling, process steam and electricity for motors, a company could use a PSEM technology. For example, the Advanced Turbine System (ATS) described in Section 4.3.2.1, could provide all these system needs. The ATS could provide reliable high-quality electricity to the PCs; ATS steam coupled with a heat exchanger could provide building heating and cooling and steam for process uses; and the turbine could be hooked directly to the drive shaft of the machine formerly driven by a motor that used grid electricity. District energy sites, where businesses group together and share electricity and steam from the same turbine, are also examples of PSEM technologies in the industrial sector. A recent study (IDEA 1997) indicates that, of the nearly 6000 current U.S. district heating installations generating more than 1.1 quads, 8% are classified as industrial. We expect that well-crafted policies to increase energy efficiency and reduce carbon will spur creative uses of both heat and power in such systems. In addition to multiple incremental improvements, we expect that some PSEM will be breakthrough technologies.

4.3.2.1 Advanced Turbine Systems (ATS) for Industrial Applications

Advanced Turbine Systems (ATS) are high-efficiency, next-generation gas turbines that produce less carbon per kWh than technologies used in conventional power markets. When commercialized in the year 2001, the emissions of CO_2 from ATS are projected to be 600 lb/MWh, 29–73% lower than conventional technologies (see Figure 4.3).[9] ATS is one of the major low-carbon technologies for the industrial sector between now and 2010 because it is a natural gas-fired turbine that cogenerates electricity and steam. The ATS's high energy efficiency stems from multiple incremental improvements applied in a novel manner.[10] Cogenerated steam displaces industrial steam boilers and their associated emissions. The steam can also be put back into the system for additional electricity generation. Further emissions reductions are due to the ATS being gas-fired and located on-site.

Although not included here because of possible double counting with Section 4.3.3.1, the ATS technology is also well suited for biomass and landfill gas fuels. The ability of ATS to burn biomass without turbine fouling and maintenance problems is being explored via new turbine materials, including ceramics and single crystal and directionally solidified turbine blades. Substantial reductions in greenhouse gas emissions will result if

ATS is fired with biomass fuel – especially in combined heat and power mode. It will require the evolution of a biomass fuel supply infrastructure, or its penetration will be limited to those industries that already have access to biomass fuels, such as forest products and some food processing sectors. We provide an example of biomass-based cogeneration in the paper industry in Section 4.3.3.

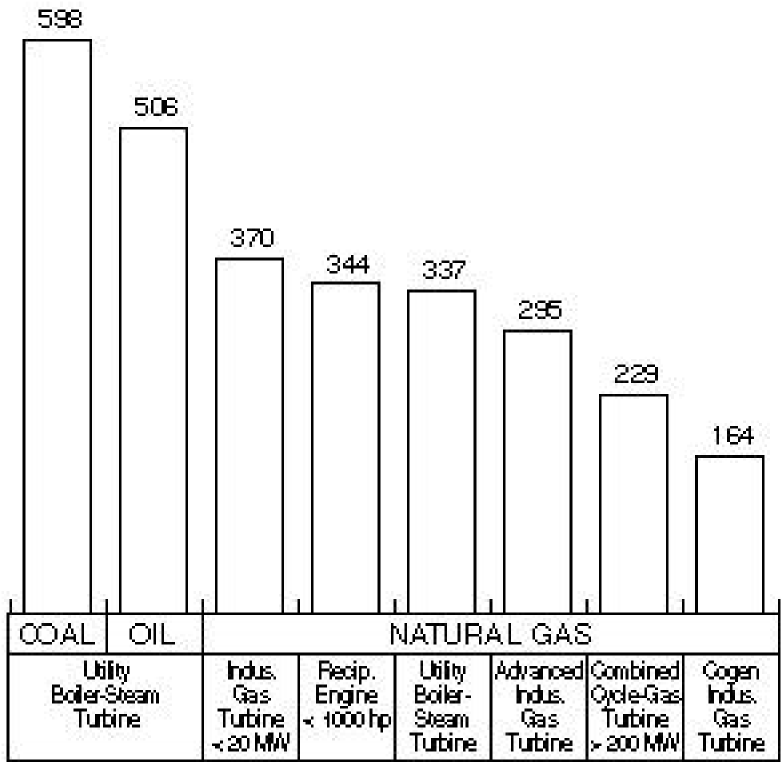
We divided the ATS "markets" into three types. The first type includes high electricity-to-thermal (E/T) ratio "power only" opportunities. These are sites where there is little or no steam demand and most of the steam from the ATS is fed back into electricity generation. The second type, "combined heat and power" (CHP), includes sites where ATS provides both steam and electricity needed on-site. The third type is a "new steam" market, where the steam and electricity needs vary.[11]

This "new steam" market is a new market not included in most energy forecasting models. It is new CHP capacity in which power and heat are not balanced and where the desire to generate electricity may be more important than getting the perfect steam match. Unlike traditional cogeneration equipment that is only efficient at a particular E/T ratio, ATS CHP systems run at high efficiency in a variety of steam and electricity configurations. As detailed in Appendix D-3, this market will spur creative uses of both heat and power. For analytic purposes, we have analyzed the "new steam" market as if it were two separate CHP and power-only markets. We decomposed new steam into traditional CHP (cogeneration assuming heat/power balance) and Power-Only (PO):

$$\textit{New steam} = a*CHP + b*PO$$

While some sector-specific studies (Appendix D-3) show *a* and *b* values around 0.5 for the entire market, the values of *a* and *b* are not well known except that they are both significant. As detailed in Appendix D-3, this decomposition also simplifies the calculation of the carbon offset. Figure 4.4 depicts simplified diagrams that allow comparison of the following: (1) a traditional steam boiler system, (2) a steam boiler that produces power using an ATS, (3) an ATS used for combined heat and power, and (4) an ATS used for power only. There are many other combinations, such as a turbine with a recuperator not shown here.[12]

Figure 4.3 Carbon Equivalent Emissions for Several Electric Generation Technologies (pounds per MWh)



Source: Gas Research Institute (1994) and Onsite Energy (1997)

Considering the large markets not yet served by this type of CHP, industry experts predict that the availability of advanced turbines will double the growth rate of new CHP capacity (Carroll 1997). This growth will greatly exceed the historic industrial market penetration of cogeneration,[13] particularly for smaller power technologies used to meet internal energy requirements. Under the efficiency or high-efficiency/low-carbon scenarios, the change in the market will occur even faster. Relatively higher prices for carbon-based fuels will encourage dispatching of electricity from low-carbon fuels, reform of environmental permitting, and utility regulations and will thus accelerate the replacement of boilers by on-site ATS cogeneration. The turbine's low installed costs, low NO_x emissions, and ability to generate electricity when steam is not needed will also contribute to the rapid growth of this new steam market.[14,15]

Table 4.12 shows the contributions of these two "markets" to the total carbon reductions. As described in Appendix D-3, the power-only carbon reductions are much smaller because we assume that the power being displaced is also quite efficient.[16] Thus, the ATS only takes credit for carbon reductions due to avoidance of transmission and distribution losses (7%). In addition, we assume the grid electricity (see utility chapter for details) and the steam boilers displaced have higher carbon emissions than those displaced in the efficiency case. For both cases, we subtracted the same traditional cogeneration that is contained in the NEMS BAU.

Figure 4.4 Simplified Diagrams of Advanced Turbine Systems in Power-Only and Cogeneration Mode Compared to Steam Boiler

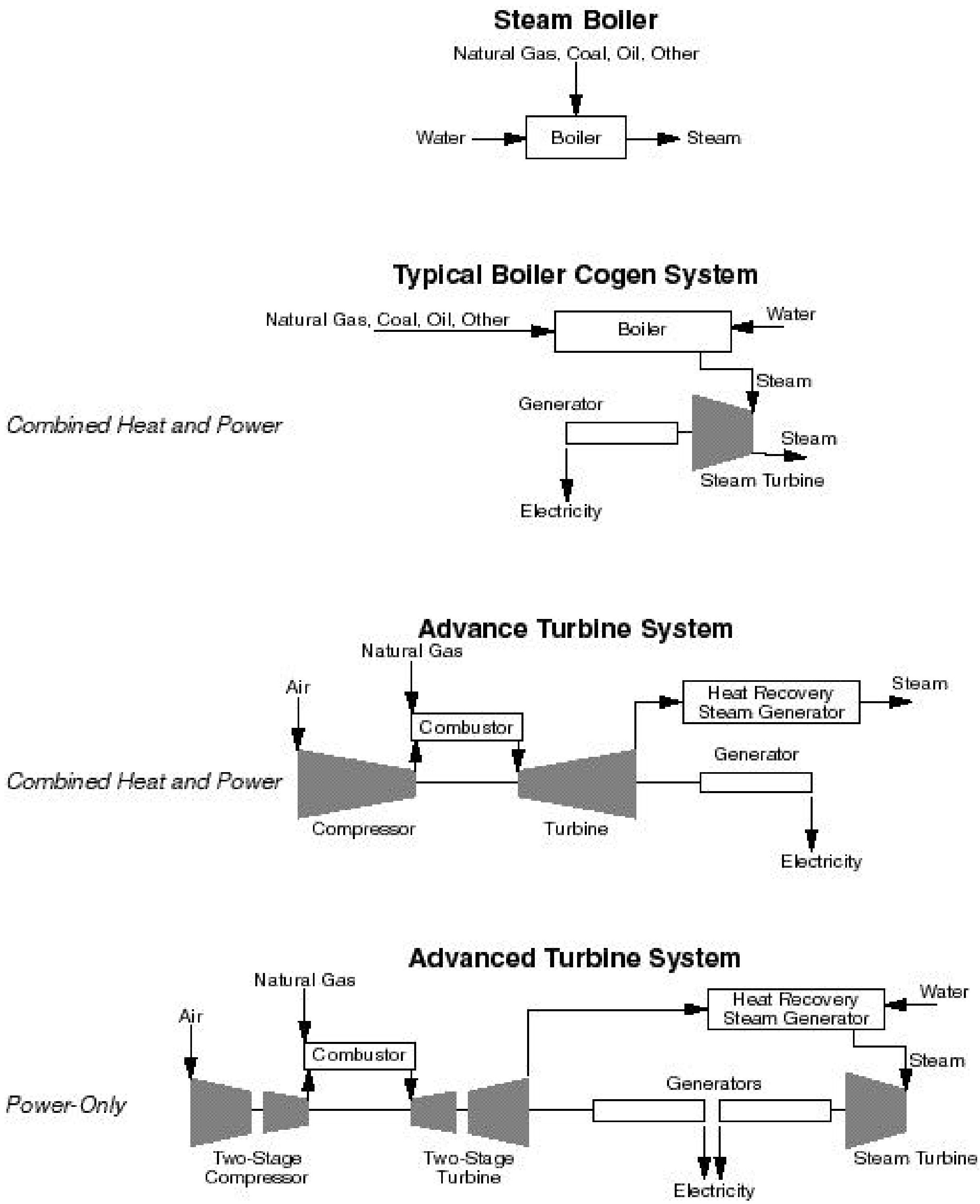


Table 4.12 Calculation of 2010 ATS Carbon Savings (MtC) and Corresponding ATS Electricity Generation (TWh)**

	Combined Heat and Power*	Power Only	Total
Efficiency	4-6 (29-59)	1 (120)	5-7 (150-180)
High-Efficiency/Low-carbon	12-21 (60-120)	2 (220)	14-24 (280-340)

Numbers may not add up exactly due to rounding. TWh shown above in parentheses.

* Excludes carbon reductions and electricity generation from traditional cogeneration that is contained in the NEMs BAU case as well as forest products biomass cogeneration which is considered in Section 4.3.3. Other ATS markets where ATS electricity generation did not result in substantial carbon savings were also excluded.

** See Table D.3-4 for details.

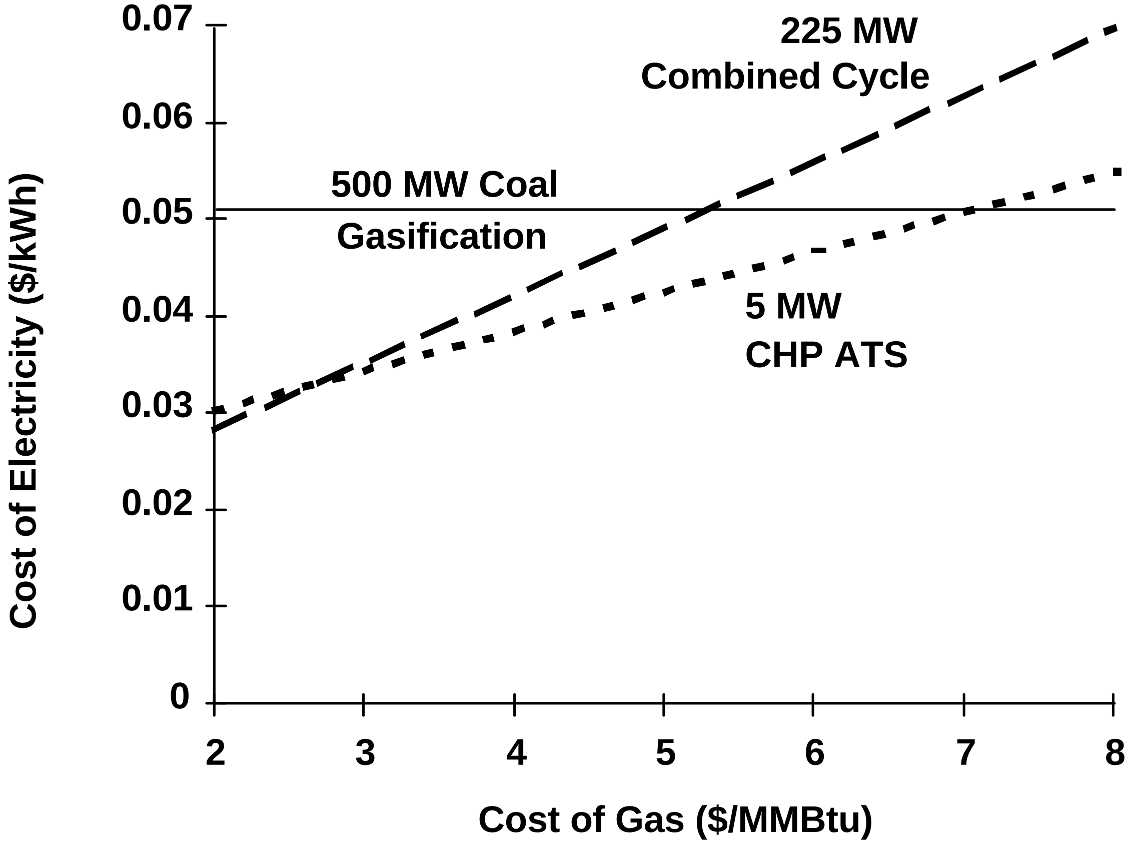
We estimate ATS carbon reductions of 5-7 MtC equivalent for the efficiency case (see Appendix D-3). This corresponds to an electric capacity of 23-27 GW and requires 0.5 TCF of additional natural gas (5% of 2010 BAU industrial demand) due to fuel switching from oil and coal biolers. For the high-efficiency/low-carbon (HE/LC) case we assume, similar to Section 4.2.2, that the penetration of ATS in these markets will double over that of the efficiency scenario. In addition, we assume the grid electricity (see utility chapter for details) and the steam boilers displaced have higher carbon emissions than those displaced in the efficiency case. This results in an ATS HE/LC carbon reduction of 14-24 MtC equivalent per year by 2010. This corresponds to an electric capacity of 42-51 GW and 1.0 TCF of additional natural gas (11% of projected BAU 2010 industrial demand).

Most of the carbon reduction comes from the fact that the ATS has a combined efficiency that is 5-10% greater than boilers. This greater efficiency also results in electricity costs that are 10% lower than current generation systems. Equipment costs are projected to be approximately $350/kW ($1.8M for a 5 MW unit) for a recuperated simple cycle unit and somewhat higher for a combined cycle unit. The major turbine manufacturers in the U.S. project that ATS will have captured 15% of U.S. power generating capacity by 2010 (Major 1997). In power-only mode, the system will be competitive against electricity prices of $0.03-0.04/kWh (Brent and Davidson 1996, Hoffman 1997). More specifically, Figure 4.5 shows that the ATS is the least-cost option for a wide range of gas and electricity prices, but it does not compete favorably with very low gas prices (where the large combined cycle turbine is less expensive) or with high gas prices (where coal gasification systems are less expensive). Note that the breakeven point between ATS and combined cycle systems is very close to the projected price of natural gas to industrial consumers ($2.60 per million Btu) in the AEO97 BAU case.

Even though the ATS is 2-3 years from being commercialized, some of the ATS manufacturers already have significant orders for ATS (Parks 1997). Since the average order/delivery time is 18 months, this means that the ATS customers are willing to wait at least 18 additional months for a superior technology. This suggests that the ATS may penetrate far more rapidly than traditional energy technologies.

In addition to carbon reduction, these turbines have other environmental benefits. ATS's low-emission combustion systems generate less than 9 ppm NOx through lean premix combustion and less than 5 ppm NOx with catalytic combustion, with no other major pollutants. When deployed in 2001, ATS systems, per MW, will produce 77–95% less NOx per megawatt than competing power generation technologies (Major and Davidson 1997b).

Figure 4.5 Electric Generation Cost Comparison



Source: Onsite Energy (1994)

4.3.3 Fuel-Switching Technologies

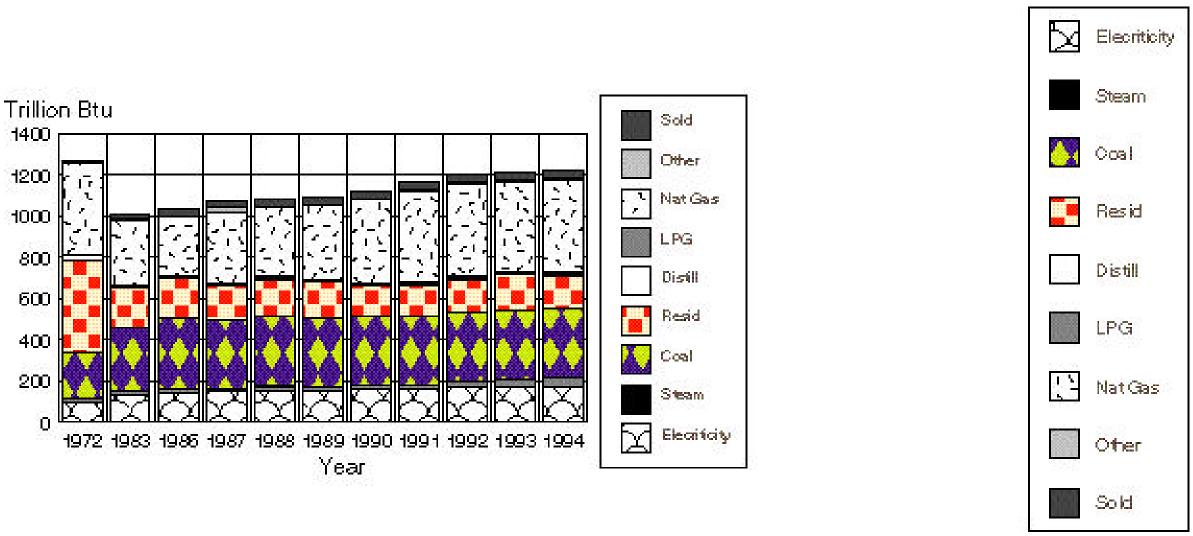
In the very near-term, fuel switching from high-carbon fuels such as coal to lower-carbon fuels such as natural gas is feasible and is already included in most energy forecasting models. In the near and medium time frame, biomass and black liquor gasification technologies described in Section 4.3.3.1 provide the option of switching from a high-carbon to a "no-carbon" fuel. Biomass is considered "no-carbon" because we assume the CO_2 produced will be rapidly resequestered by growing biomass feed stock (see Chapter 7 for more detail on biomass). These technologies can also be considered PSEM technologies because they replace inefficient biomass boilers and grid electricity with biomass gasification cogeneration. Black liquor technology utilizes black liquor gasification instead of improved efficiency recovery boilers (which are the replacements implicit in the modeling calculations of Section 4.2.2). Biomass gasifiers replace inefficient boilers for steam and electricity. These technologies allow the industry to generate more of its own electricity which leads to the offset of purchased electricity. The extra generation of biomass-based electricity is not included in the modeling calculations of Section 4.2.2 and is responsible for the carbon offsets calculated here. Although no examples are provided, other renewable energy-powered industrial technologies (e.g., solar detoxification) could also be considered low-carbon fuel-switching technologies.

4.3.3.1 Integrated Gasification Combined Cycle Technology for the Forest Products Industry

Integrated gasification combined cycle (IGCC) technologies can significantly impact the carbon reductions expected in the forest products industry in two ways: (1) by increasing energy self-generation and (2) by better utilizing residues from the forest management and manufacturing processes. Potential offsets of carbon emissions by 2010 are approximately ten MtC equivalent per year in the high-efficiency/low-carbon scenario. The efficiency scenario could achieve offsets of about 5 MtC equivalent per year. To achieve the carbon reductions in the high-efficiency/low-carbon scenario, it will be necessary to facilitate early commercialization to reduce investment risk and provide an incentive for industry to commit the resources necessary to implement these advanced technologies.

The pulp and paper industry purchases 43% of its energy and uses a diverse mix of resources including electricity, steam, coal, residual and distillate fuel oil, liquid propane gas, and natural gas. In 1972, the industry used oil for nearly a quarter of its purchased energy but this proportion decreased to 6.9% in 1994 by doubling purchased electricity and increasing coal purchases by 50%. This complex purchased fossil fuel and energy pattern is shown in Figure 4.6.

Figure 4.6 Purchased Energy in the U.S. Pulp and Paper Industry by Fuel Type, 1972 1994



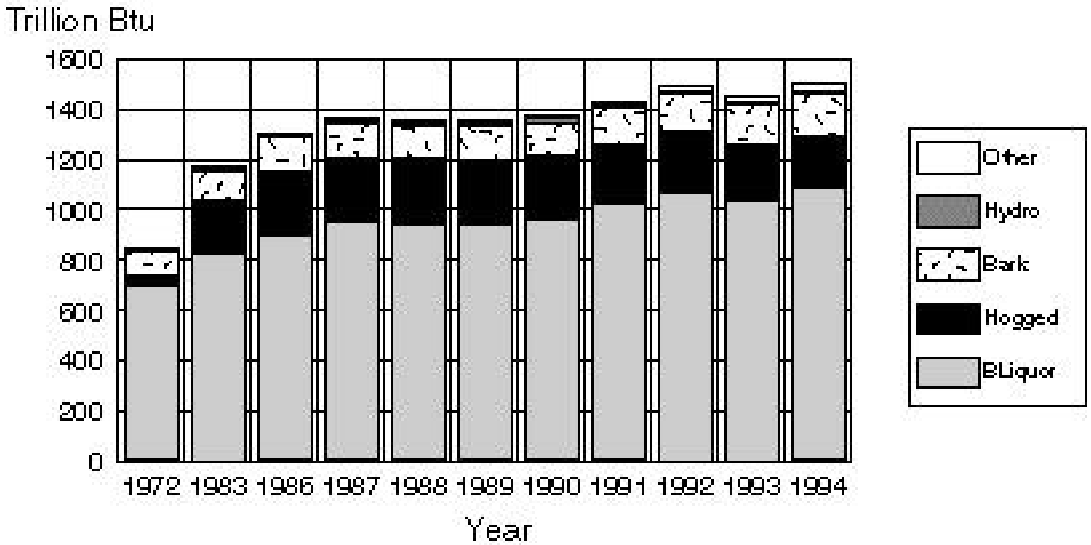
Source: Miller Freeman, Inc. (1972–1994)

The industry self-generates the remaining 57% of its required energy through the recovery of energy and chemicals in spent black liquor, use of residues such as hog fuel and bark in boilers, and cogeneration of heat and power (see Figure 4.7). The American Forest and Paper Association (AF&PA) estimates that use of these energy sources displaced more than 227 million of barrels of oil in 1994 (Miller Freeman, Inc. 1996).

These fuel switches, increased cogeneration, and energy conservation measures resulted in a decrease in energy intensity. Even though total energy consumption increased over the period 1972–1994, energy consumption per ton of product output decreased by 21% (Miller Freeman, Inc. 1997).

Two opportunities for further improvements were analyzed in detail: increased self-generation from black liquor and increased recovery of usable energy from hog fuels and bark coupled with increased recovery of forest residues and pre-commercial thinnings. Increased self-generation offsets purchases of electricity and coal, and thus offsets CO_2 emissions.[17] These higher-efficiency processes could also increase the industry's electricity production for return to the grid.

Figure 4.7 Self-Generated Energy in the U.S. Pulp and Paper Industry by Fuel Type, 1972 1994



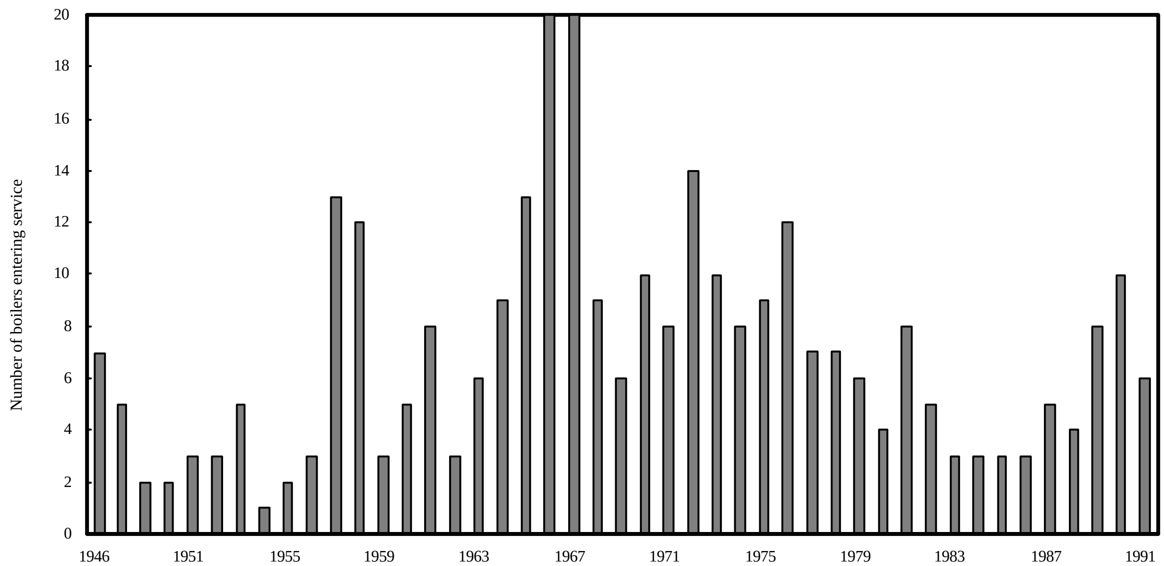
Source: Miller Freeman, Inc. (1972–1994)

Kraft Recovery Boiler Replacements. Traditionally, about 40% of the energy used in a mill is generated from burning the lignin solids. Lignin is the portion of wood that holds the fibers together and makes them stiff. The pulping process separates the lignin from the pulp fiber. The lignin is a dilute solution which is evaporated and burned in a boiler designed to recover the pulping chemicals; heat from combustion is used to make steam. Some of the steam is used to supply the mill's needs and some is used to generate electricity for the mill.

In the black liquor gasification combined cycle process, a little less steam is generated but two to three times more electricity is produced. Process changes designed to make mills more environmentally friendly tend to change the balance of energy forms that a mill uses. Mills are using less steam energy and more electrical energy; the combined cycle process fits right into the future process needs.

The technology is coming on the scene at an opportune time because most of the existing recovery boilers in the industry are reaching the end of their useful safe operating life. The majority of recovery boilers were put into service between 1955 and 1980, with a peak period around 1967 (see Figure 4.8). For environmental and safety reasons the industry is developing alternative technologies in anticipation of replacing these boilers after a 40-year service life. The need for capital replacement creates an opportunity for penetration of new, high-performance, environmentally acceptable technologies. The gasification component of the replacement technology is already at the early stages of commercial deployment, mainly as a means of expanding mill electric generation capacity in situations where the current recovery boiler limits throughput. There is a need for chemicals recovery cycles to be tested and for the integrated cycle to be demonstrated. Expediting RD&D could allow significant carbon emissions offsets by matching the timing of technology development and commercialization to the need for boiler replacement.

Figure 4.8 Kraft Boilers in Service in the United States



Source: American Forest and Paper Association

A major barrier to the adoption of black liquor IGCC systems is the central role that the current recovery boiler plays in the chemical and energy recovery of the mills. Typically, this part of the pulping process has to reliably operate at full throughput with annual capacity factors of greater than 95%. A further barrier is the need for process heat. Increasing the electricity output will require a concomitant improvement in process heat utilization since the steam output of the black liquor IGCC system will be 21% less than that of the recovery boiler, even though the electricity output is effectively doubled.

Replacement of the current recovery boilers by new technology based on gasification to recover both process chemicals and the energy content of the dissolved lignin has the potential to produce 104 TWh of electricity per year, offsetting about 100 Mt of CO_2 emissions. Full replacement of the current recovery boiler capacity at the 1996 production volume would offset 26 MtC equivalent per year. Based on a rate of recovery boiler replacement that assumes a 40-year life for the existing recovery boilers, the 2010 displacement is 5.2 MtC equivalent per year, and the 2020 displacement is 8.7 MtC equivalent per year. The methodology used to determine the replacement rate, on which the projected carbon reductions are based, is discussed in Appendix D-4. The black liquor IGCC system is designed to meet New Source Performance Standards (NSPS), and would also have low NO_x and SO_x emissions. Investment costs for integrated gasification combined cycle are forecast to be less than those for replacement with a conventional recovery boiler system, on a dollar per kilowatt-hour basis. It is anticipated that IGCC systems would be competitive against electricity purchases at $35/MWh.

Residual Biomass Boiler Replacements. Food processing, wood products, and pulp and paper are industries that generate large amounts of residual biomass (e.g., waste wood and bark). While much of this biomass is currently being used, if it were gasified and used to cogenerate steam and electricity, it would substitute for (largely) fossil fuel-produced electricity. Advances in turbine efficiency (see Section 4.3.2.1) make this an economically attractive option. By using residues from pulping processes as well as biomass from forestry operations in conjunction with gasification and combined cycle technologies, 2.3 GW of capacity can be put in place by 2010, offsetting 4.8 MtC equivalent per year. This would represent about one-third of the potential mill conversions projected to need replacement by that time. Because of the stage of development of the technology and its markets, a conservative estimate would reduce replacements from one-third to one-quarter of the potential mill conversions. Using the more conservative penetration, the carbon replacement potential from gasification of residual biomass is 3.6 MtC equivalent per year.

Approximately 200 mills are already producing heat and some power from the use of residual biomass in their processes.[18] The majority of in-place boiler units entered service between 1965 and 1975 and need replacement; they are either reaching the end of their service lives or they may have difficulty meeting environmental regulations (or both). Residual biomass gasification can penetrate this replacement market with the potential to double the net rate of electricity generation – from a generation efficiency of about 15% to 35%. The technology is already in the early stages of commercialization with the first 18 MW IGCC operating in Sweden. Prototype units are being demonstrated elsewhere in Scandinavia and the United States.

The current cost of this technology is approximately 50% over the plant cost when the technology is mature. Incentives will be necessary to facilitate entry of the technology into the replacement market. One proposal is a capital cost buydown to bring technology costs down.

The gasification system is designed to meet New Source Performance Standards (NSPS) and would have low NO_X and SO_X emissions. Biomass growth and harvesting would be according to best practices, and to some extent the biomass fuel source could include materials that are currently landfilled and thus contribute to landfill methane emissions.

4.3.4 Low Process Carbon Technologies

Low-process carbon technologies reduce or avoid the emission of non-combustion CO_2 and other greenhouse gases in industrial and other processes. As shown in Table 4.13, 92% of the carbon equivalent emissions of process carbon are due to non-CO_2 greenhouse gases that have far higher global warming potentials (GWP) than CO_2.

4.3.4.1 Industrial Sources of Non-CO_2 Greenhouse Gasses

Although non-CO_2 industrial emissions of greenhouse gasses are small by weight, they have GWPs that range from 21 for methane to 23,900 for sulfur hexafloride (SF_6). Figure 4.9 shows the relative contribution of these other gases in MtC equivalent. The largest non-CO_2 greenhouse gas contribution is from methane (CH_4), which is responsible for 177.5 MtC equivalent and has a GWP of 21. Next is nitrous oxide (N_2O) which is responsible for 39.1 MtC equivalent and has a GWP of 310. Finally, in 1994, various halocarbons and other engineered chemicals amounted to 29.5 MtC equivalent. These engineered chemicals are a source of concern since their emissions are growing rapidly – and the United States is the major source. As shown in Table 4.13, emissions of these other greenhouse gases from agriculture (27%), mining/energy extraction (25%), service (24%), and transportation (8%) sectors are important.

The manufacturing sector accounts for 14% of carbon equivalent emissions due to other greenhouse gases. The manufacturing processes that generate GHG emissions include:

Waste emissions of CF_4, C_2F_6, C_3F_8, NF_3, and CHF_3 from plasma etching, chemical vapor deposition (CVD), and CVD chamber cleaning in semiconductor manufacturing;

Waste emissions of SF_6 from the manufacture of transformers, circuit breakers/load-shedding devices, and electrical distribution components where SF_6 is used as an insulator;

By-product emissions of N_2O from adipic acid manufacture;[19]

Waste methane emissions from production of ethylene and styrene;

PFC emissions from aluminum production (see Section 4.3.4.3); and

Waste emissions of SF_6 from magnesium casting in which SF_6 is used as a cover gas to protect against catastrophic oxidation.

Table 4.13 Process Carbon Emissions and Energy Use by Sector

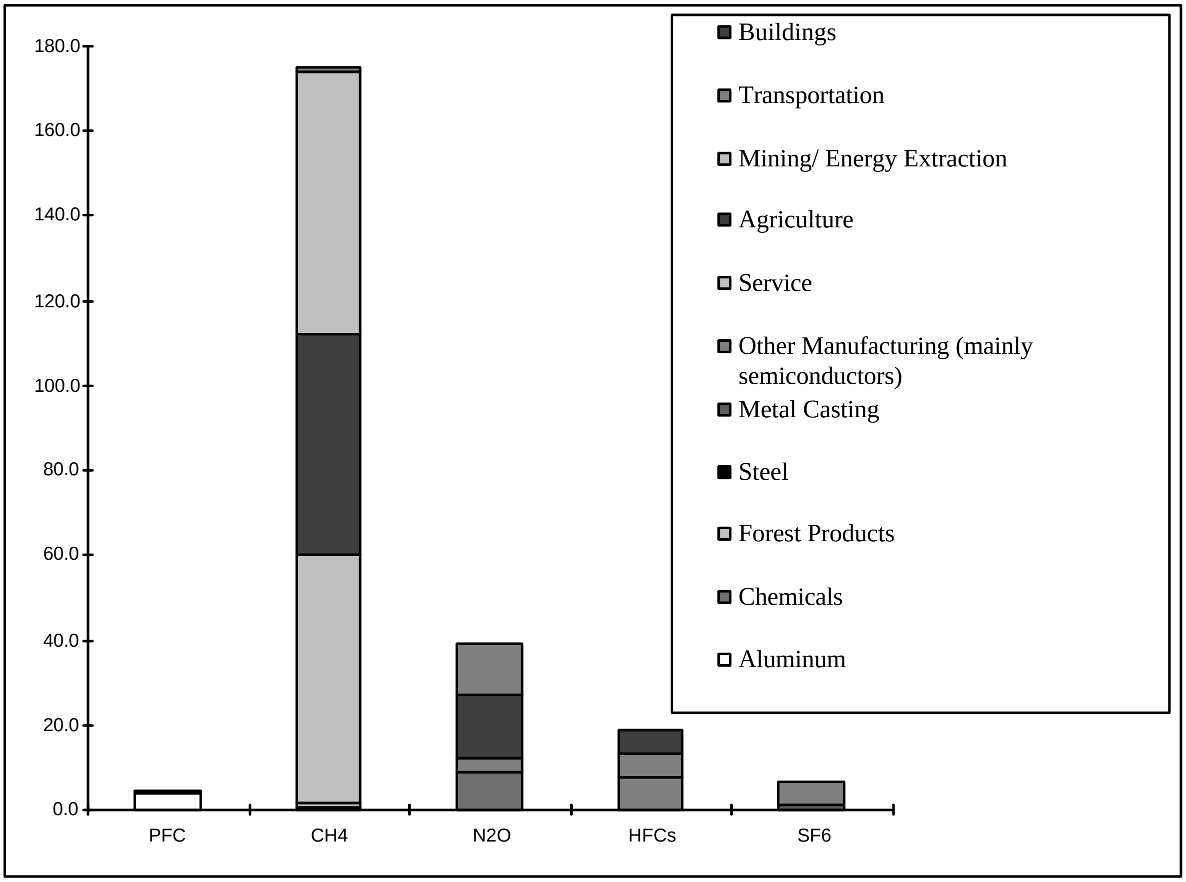
	Carbon Emissions (MtC equivalent)			
	Process CO_2*	**Other GHG Carbon Equivalent**	**Total Carbon**	**Energy Use (quads)**
Manufacturing	18.4	33.0	51.4	22.4
Service	0	58.2	58.2	
Agriculture	0	66.7	66.7	
Mining/Energy Extraction	0.9**	61.5	62.4	
Construction	2.0	0	2.0	
Subtotal Industry	**21.3**	**219.4**	**240.7**	**32.6**
Buildings	0.0	5.3	5.3	33.7
Transportation	0.0	19.0	19.0	25.5
Total	**21.3**	**243.7**	**265.0**	**91.8**

*Source: EIA 1996

**Gas flaring.

While none of the manufacturing emissions are particularly large, we note that global emissions of SF_6 are increasing at a rate of 7–8% per year. This is of particular concern because SF_6 has a very high global warming potential of 23,900 and an expected lifetime of 3,200 years, making it a very potent greenhouse gas. Thus SF_6 emissions alone are increasing at a rate of 0.5 MtC equivalent per year (EIA 1996). Several emerging technologies may be immediately helpful in avoiding these emissions. For example, applications of high temperature superconductor technologies include transformers and current limiters that act as circuit breakers (Platt 1997). Many of these emissions are seen not only in energy-intensive industries but also in “high-tech” manufacturing industries. These non-energy-intensive industries include semiconductor manufacturing and equipment manufacturing for the electric utility industry. Due to scope and time constraints, technology options to reduce these emissions are not addressed in this report but are an important area for future analysis.

Figure 4.9 Non-CO_2 Greenhouse Gas Emissions in the United States (MtC equivalent)



Source: EIA (1996)

4.3.4.2 Process CO_2 Emissions

Compared to other greenhouse gases, process CO_2 emissions are relatively small, accounting for only 9% of process carbon emissions and less than 5% of industrial combustion-related CO_2 emissions. Overall, the industrial sector directly emitted about 23 MtC from CO_2 industrial processes.

The primary industrial processes that generate process carbon emissions include:

The calcination of limestone in cement manufacture (largest single source);

The manufacture and consumption of limestone (e.g., in lime kilns, iron smelting, steel making, glass manufacture and flue gas desulfurization);

Dolomite consumption;

Soda ash manufacture and consumption (e.g., in glass manufacture, flue gas desulfurization, and chemicals production);

CO_2 manufacture;

Gas flaring; and

Aluminum production.

There has also been a disproportionate increase in process CO_2 emissions relative to combustion-related CO_2 emissions. Over the past eight years, process CO_2 emissions have increased nearly 16% while combustion-related CO_2 emissions have increased only 4%. However, these process carbon data are highly uncertain due to their variability across sites due to non-uniform measurement technique. For example, the carbon emissions could be flat in reality but appearing to rise because measurements are more comprehensive today.

The following sections describe carbon savings in the aluminum and cement industries that are possible given aggressive RD&D and commercialization strategies.

4.3.4.3 Low-Carbon Technologies in Primary Aluminum Production

Because of the very high chemical stability of aluminum oxide and other aluminum compounds, the production of aluminum metal was not feasible until the nineteenth century when electrical power generation facilities became available to permit commercial electrolytic reduction operations. Creation of today's world-wide aluminum industry occurred after the simultaneous inventions by Hall and Heroult of a process for high-temperature reduction of aluminum oxide dissolved in a molten fluoride salt using a carbon anode which is consumed during the process reacting to form carbon dioxide.

The global warming potential associated with aluminum production results from several factors

First, carbon dioxide is generated at fossil fuel plants that produce the electricity required for the electrolysis process.[20] State-of-the-art Hall-Heroult cells achieve power consumption levels as low as 13,200 kWh/tonne of aluminum produced; however, most aluminum plants require more electricity per tonne of product.

Second, the production of one metric ton (or tonne) of aluminum leads to the generation of at least 1.22 tonnes of process carbon dioxide (or 0.33 tonnes of carbon) from the reduction cell operation.

Third, global warming effects also result from the generation of perfluorocarbons (CF_4 and C_2F_6) during instabilities in the cell operation (called "anode effects") that occur when oxide concentration in the cell bath becomes undesirably low. In 1994, aluminum smelting is estimated to have emitted the equivalent of 4.2 million metric tons of carbon equivalent, from perfluorocarbon (PFC) byproducts (EIA 1996).

Further reductions in the levels of greenhouse gas emissions associated with primary aluminum production will require:

1. Development of reduction technologies that require less energy for primary metal production;
2. The development of inert, non-carbonaceous anodes that are not consumed through the reduction process; and
3. The development of improved cell designs and operating control strategies to reduce PFC emissions.

On the basis of ongoing research on aluminum reduction technology, the desired improvements will require the development and commercialization of retrofit advanced cell technology with wettable cathode and inert anode components. Two scenarios have been developed: an efficiency scenario, based on the development and use of wettable cathodes with conventional carbon anodes, and a high-efficiency/low-carbon scenario, based on the addition of inert anodes to the advanced cell.

Under both the efficiency and high-efficiency/low-carbon scenarios, R&D on advanced aluminum production cells would be funded by both the federal government and the private sector. However, under the high-efficiency/low-carbon scenario, the development of inert anodes and the associated control systems would be pursued more aggressively. In either case, alternative cathode and anode materials, advanced cell designs, and advanced operating control methods would be developed with the overall goal of reducing the cell voltage (electrical energy requirements and associated power plant CO_2 emissions), eliminating CO_2 cell emissions, and significantly reducing emissions of PFCs arising from cell operating instabilities. In the discussion below, we analyze the incremental energy efficiency improvements and reduced carbon gas emission savings from these advanced low-carbon technologies for primary aluminum production.

Under the efficiency scenario, the wettable cathode part of the advanced cell is forecast to be ready for commercial operations by approximately 2005. Conventional, non-wettable cathode cells operate with thick metal layers above the cathode surface. In contrast, use of wettable cathodes permits cell designs in which product metal can be drained from the cathode to collection sites within the cell leaving only a thin film of metal at the cathode surface. Normal undulations at the metal surface resulting from electromagnetic stirring and gas bubble driven circulation are virtually eliminated with wettable cathodes permitting cell operations with reduced anode-cathode spacings. In combination with advanced process sensors and control systems to optimize cell operation, the potential energy savings are estimated to be as high as 15–20% over conventional cells (DOE 1990). These same sensors and control systems would yield reduced levels of PFC gas emissions. These technologies will be designed for simultaneous or independent retrofit use on existing cells.

The high-efficiency/low-carbon scenario forecasts the additional development of inert anodes. The most promising materials presently being evaluated are ceramic/metal composites consisting primarily of nickel oxide and nickel ferrite with a copper/nickel metal phase (Windisch and Strachan 1991). These permanent anodes would also eliminate CO_2 emissions associated with the manufacture and consumption of carbon anodes. If successful, the advanced cell would result in an approximate 27% reduction in the electricity requirements for primary aluminum production.

Research would be scheduled so that commercial-scale demonstration tests (individual commercial sized reduction cells up to the actual conversion of an operating potline) would be in operation by approximately 2005. To re-engineer an existing smelter site with radically different production may require a capital investment ranging from $500,000 to $2 billion. For investments of this scale, conclusive demonstrations defining operating performance, operating costs, and equipment lives must be completed to achieve industry acceptance and widespread adoption.

The economic feasibility of the advanced technology would be enhanced if federal policies promoting further reductions in carbon emissions were established. Even without such policies, the U.S. aluminum industry has expressed a goal of eliminating process CO_2 emissions in primary aluminum (Energetics 1997). Furthermore, trends toward increased use of aluminum in the transportation sector to improve vehicle fuel efficiency through weight reduction could significantly increase demand for primary aluminum, further increasing the economic feasibility of the advanced cell technology.

Under the efficiency scenario, we assume that five of the existing 22 aluminum plants operating in the U.S. (American Metal Market 1997) are retrofitted to use the advanced wettable cathode cell. With an average plant capacity of 190,000 tonnes of aluminum per year and an average annual electricity consumption of 13,200 kWh per tonne of aluminum, electricity efficiency improvements of 17% in these five plants would result in 0.19 million tonnes of reduced carbon-equivalent emissions in 2010.[21] This is 0.09 MtC more than the efficiency scenario described in Section 4.2.2.[22] In addition, the PFC emissions from anode effects are projected to be halved in those five plants where wettable cathodes are installed. This would represent an 11.4% (or 0.48 MtC) reduction in the aluminum industry's carbon equivalent emissions of 4.2 MtC.[23]

Under the high-efficiency/low-carbon scenario, use of the advanced, inert anode by 10 of 22 plants could lead to reduced carbon emissions by 1.6 MtC equivalent, of which 1.00 metric tonnes of carbon savings are due to the reduced consumption of electricity.[24] This is equivalent to 0.67 MtC over the high-efficiency/low-carbon scenario described in Section 4.2.2.[25] An additional 0.6 Mt of carbon savings result from the elimination of carbon emissions from the production cell.[26] The use of inert anodes to eliminate the process CO_2 emissions from smelting was not considered in Section 4.2.2; thus, all of these carbon reductions are accounted for here. In addition, the PFC emissions from anode effects are projected to be eliminated in those 10 plants where inert anodes are installed. This would represent a 45.5% (or 1.91 MtC) reduction in the aluminum industry's carbon equivalent emissions of 4.2 MtC.[27]

These carbon reduction estimates are summarized in Table 4.14. The advanced aluminum production cell in the efficiency scenario accounts for 0.6 MtC (or 0.5 to 1.0 MtC) of reductions above the carbon reductions already incorporated in Section 4.2.2. The high-efficiency/low-carbon scenario accounts for 3.2 MtC (or 3 to 3.5 MtC) more than the carbon reductions already incorporated in Section 4.2.2. Technical details of the advanced aluminum production cell are discussed in Appendix D-6.

Table 4.14 Carbon Reductions from Advanced Aluminum Production Cells, in 2010 (MtC)

Sources of Carbon Reductions	Efficiency Scenario	High-Efficiency/Low-Carbon Scenario
Electricity Savings		
•Included in Section 4.2.2	0.1	0.3
•Increment above Section 4.2.2	0.1	0.7
Cell Production	0	0.6
Reduced Perfluorocarbons	0.5	1.9
Total	**0.7**	**3.5**

4.3.4.4 Replacing Cement Clinker with Solid Wastes

The cement industry is the single largest source of U.S. process CO_2 emissions and a major energy user. The annual process CO_2 emissions from the U.S. cement industry are 9–10 MtC equivalent (EIA 1996). Energy-related CO_2 emissions are of similar magnitude depending upon the cement kiln technology. Some estimates indicate that each ton of cement clinker produced results in the direct emission of one ton of CO_2. Other estimates with different kiln technologies have a much higher energy/process CO_2 ratio. Of the process emissions, about 60% of the direct emissions are from calcination of limestone and the other 40% are from combustion products from fossil fuels that directly or indirectly supply the energy for calcination.

Nearly all cement in the United States is made from ground clinker intermixed with gypsum. One technically straightforward and cost-saving way to reduce energy input and carbon emissions per ton of cement is to replace some of the clinker with abundant utility and steel plant wastes such as fly ash or granulated blast-furnace slag. Such a replacement makes cement with somewhat different properties, but still a satisfactory building material. Most European countries allow such cements and have found that these cements last longer and are more tolerant to salt water than pure clinker cement. However, U.S. product specifications (Standard Specification for Portland Cement, ASTM C150) do not allow any extra ingredients in cements. These specifications are difficult to change because the small minority of those who might lose markets (e.g., non-integrated cement producers) can easily stop changes under the current system. A recent study (Sauer 1997) estimates that changing the U.S. specifications to permit inter grinding could reduce both energy and process CO_2 emissions by 5–20% per year by reducing demand. If the specifications were changed, it is likely the new technology could be rapidly adopted by U.S. cement manufacturers, especially the multi-national firms that are already using this type of cement in Europe. Under the high-efficiency/low-carbon scenario, the barriers to this technology could be overcome. In addition, there would be motivation to conduct further research, development and demonstration activities exploring a wide range of cement inter grinding materials and percentages and to ensure that they provide the same or improved performance. Based on these studies and assuming a low-carbon, aggressive R&D scenario, our estimate is that by 2010, 1–2 MtC equivalent of industrial carbon emissions could be avoided due to cement inter grinding and replacement.[28]

Though the manufacturing process has remained the same, the U.S. cement industry has changed over the past 20 years. The number of kilns in operation has dropped by 50% since 1975. There has been a 28.3% improvement in fuel efficiency since 1975, dropping the energy required per metric ton of cement from an average of 7.26 MMBtu in 1975 to 5.20 MMBtu in 1994. Over 60% of U.S. clinker capacity is foreign owned or affiliated with foreign firms, and most of these are integrated European cement companies. The primary customer, accounting for 60% of shipments, is the ready-mix concrete industry which supplies concrete, mixed to customer specifications, to construction sites (Bureau of Mines 1994). Concrete typically contains 10–15% cement as a binder. Cement demand is projected to grow at 1% per year, half the rate of GDP.

On average, energy accounts for between 30 and 40% of cement manufacturing cost. Electricity represents about 10% of energy input, but frequently accounts for close to 50% of total energy cost. Integrated cement producers and ready-mix concrete suppliers would benefit from replacing high cost clinker with low- or negative-cost materials. The cement industry is already a leader in waste utilization. More than half of plants responding to a 1994 survey reported the use of one or more types of waste as fuel. This technology could, however, speed the decline of non-integrated cement producers.

In addition to reducing CO_2 emissions, this technique also reduces NOx, SO_2, and particulate emissions associated with electricity use. It also reduces solid waste by replacing quarried raw materials with wastes and by-products such as fly ash, foundry sands, and mine tailings.

4.4 PROVEN INDUSTRIAL TECHNOLOGIES

Although our forecasting methodology does not draw directly from detailed representation of individual technologies, the forecast savings that are expected in each sector will be drawn from a variety of sources of new technologies and business practices. This section illustrates the range of commercially available and near commercial innovations that firms in these industries can draw upon to achieve the additional reductions in energy use that are considered feasible in the HE/LC case and could contribute to this projected decline. In addition, we provide examples of technologies that directly displace carbon in Section 4.3.

We provide illustrative examples of currently-available technologies that we believe could be integrated into industry to provide the savings suggested by the model simulations for each energy-intensive industry; we also provide examples of cross-cutting technologies. We describe how each technology is used and from what type of efficiency it draws its energy and cost savings.

Some technologies recover or reduce the production of waste heat in high-temperature applications while others optimize the process load to the energy-using equipment. Many of the most successful technologies have multiple benefits, including pollution prevention or productivity-enhancing features. A technology that reduces product loss or increases process throughput will often reduce labor or material costs as well as energy costs. For example, continuous casting, widely adopted by the steel industry, is cost-effective based on its energy savings alone but industry has adopted continuous casters in large measure because of the improvement in steel quality and because it reduces losses. Similarly, impulse drying, an emerging technology, saves energy, but also allows additional throughput on the paper-making machines and will improve the quality of the product.

While it is felt that these technologies are representative and have the potential to be readily accepted by industry, the estimates of energy savings provided below *do not represent any industry consensus* of the relative difference between the new technology and average practice. Instead we rely on available, published literature that assesses the performance of these technologies and business practices.

The diversity of industries, businesses, plants, and processes implies that not all of these examples will be universally cost-effective, or even applicable. Site- or plant-specific constraints may prevent the use or economic acceptability of a technology for retrofit applications that would be readily accepted in a new plant design. In many of the most energy-intensive process industries, few green-field plants are being built in this country, further limiting some applications. While we do not consider explicitly the economics of *when* to replace old equipment, we understand that a variety of considerations enter into this business decision, including:

How learning curves tend to continually lower the costs (including energy costs) as cumulative production experience with new technology is gained;

Countervailing factors like "wear and tear" that tend to increase costs over time;

How the introduction of new equipment can alter the economics of existing equipment; and

Available design trade-offs between capital and other costs, especially energy costs.

New and replacement capacity will be put into place at many existing plants based on these and other decision variables. The opportunity for new technology to be adopted occurs at the point in time when these decisions are made. It is at this point that energy prices and capital discount rates can influence the decision to purchase new technology and thus the adoption of technologies for which examples are given below.

Many of these technology examples exhibit energy savings of more than 5-10% relative to current average practice, but the turnover rates of the capital stock in the energy- and capital-intensive industries require our projections to take this into account. In 13 years, many of these technologies (and many others not listed here) are capable of reaching higher levels of penetration, but most will not achieve 100% penetration. In addition, the technology examples often account for some fraction of the energy use in that sector. However, the examples show that there are many ways in which efficiency in industry can be increased, given the right incentives.

Brief descriptions of energy-efficient technology opportunities for the industrial sector are provided in the following sections; more details are available in the associated appendices and references.

4.4.1 Cross-Cutting Technologies

There are a variety of cross-cutting technologies that are not process- or product-specific in operation in industry. Some include lighting and heating, ventilation, and cooling technologies that are also commercial applications and are not discussed here (see Chapter 3). Others include sensors and computer control systems which have a common underlying technology, but have a variety of configurations and benefits depending on the industry. There are two major ways that all of industry can benefit from improved efficiency: cogeneration and improved motor systems.

4.4.1.1 Combined Heat and Power

Combined heat and power (CHP) is the joint production of useful steam and electricity, either for on-site use or sale back to the electric grid. There are substantial thermodynamic advantages to the joint production of heat and power that could greatly reduce generation losses from traditional power production and would reduce carbon emissions system-wide. The advantage of such an approach is that little additional fuel is required for the electricity generation over that required for simple steam production. Thus, the efficiency for use of the thermal energy available from the fuel is higher than with separate electricity generation and steam production, and the net greenhouse gas emissions can be reduced by the application of cogeneration. Based on a typical boiler configuration, the gas turbine with heat recovery steam generation is typically the most cost-effective (Boyd et al. 1996). CHP can also help reduce carbon through fuel switching to low- or no-carbon fuel. Under the BAU case, CHP power production will grow to 333 TWh by 2010. See Section 4.3.2 for an example of a CHP system that can reduce carbon emissions far more than predicted in the BAU.

4.4.1.2 Motor Systems

Energy-efficiency opportunities associated with electric motor drives derive not so much from the replacement of motors with high-efficiency motors as from energy-conscious design throughout the system employing the motor drive. Such a systems approach (see Section 4.3.2) has also resulted in significant non-energy savings when motor systems are improved.[29] The system includes power supply lines, controls, motor feed cables, the electric motor, the drive and transmission system, and the driven load. Each of these system elements may present a significant opportunity to conserve energy.

The power supply and control systems affect efficiency in three ways. First, power is consumed by resistance losses in the supply wires. Second, losses in the supply wires may contribute to voltage imbalance in the power supplied to a polyphase motor, leading to reduced efficiency and possible motor damage. Third, other system loads and certain control devices, particularly adjustable speed drives, can distort the sinusoidal AC voltage provided to the motor, resulting in efficiency and torque losses, vibration, and possible bearing damage, which is accompanied by increased friction.

Losses associated directly with the electric motor include electrical resistance losses, magnetic losses, friction and air flow losses, and stray losses associated with manufacturing quality limitations. High-efficiency motors address these losses, though efficiency improvement over standard motors may only average 5% to 7%. While an electric motor consumes less than full power when the load it serves is less than the motor rating, the efficiency of the motor declines dramatically as the load declines below 40% of rated load. Since motor over sizing is common practice, this provides a significant efficiency improvement opportunity.

Losses associated with drive systems are frictional losses in belt and gear systems. Higher losses are associated with greater speed reductions, which may improve the relative economics of adjustable speed drives (motor speed control). While drive transmission efficiency may be well over 90%, it may be below 50% as well. Thus, drive system design may offer more savings opportunity than motor replacement.

The most important savings opportunities will often lie in specification and design of the driven load. In the extreme, process changes may eliminate the need for the load entirely or equipment substitution can reduce power requirements. For instance, mechanical conveyors may be used rather than pneumatic conveyors at a substantial energy savings. More commonly, proper selection of loads such as fans, pumps, and compressors to match the intended application requirements will result in the equipment operating at higher efficiency and presenting less load to the electric motor. Then, proper matching of the remaining load to a motor, perhaps with variable speed control, will result in optimal overall system efficiency.

4.4.2 Pulp and Paper

Paper manufacturing was one of the most energy-intensive industries in the United States in 1994, using more than 18,500 Btu per dollar value of shipments. The manufacturing of paper requires that a fiber source, normally wood, be chipped, digested, bleached, and then formed as a slurry from which paper or board is made. Once formed as paper, the product must be dried. Large amounts of steam and power are used to debark and chip the wood, digest the wood, bleach the pulp, and dry the paper products. Much of this energy source (over 50%) comes from the reprocessing of lignins from the wood, bark, and unusable portions of the tree. In lumber and wood products, the fraction of biomass energy sources is nearly 70%.

In paper manufacturing, any technology that will economize the use of steam, reduce the need for heat, better utilize the biomass fuel sources available, or help to balance both steam and power needs will improve the performance of the industry. The technologies that hold promise to reduce energy and carbon emissions in the near-term continue to economize on the use of heat. Longer-term options alter the balance between steam and power. The most promising near-term options are discussed below.

Impulse Drying: Impulse drying reduces the huge energy requirements of evaporative drying by removing more water in the pressing section and reducing the amount of water which must be evaporated. The total energy savings for full implementation of this technology are estimated to be approximately 0.25 quad/yr. Without an invigorated effort, the net energy savings are estimated to be about 12 trillion Btu annually from a market penetration of only 65 drying units by 2020. Impulse drying methods allow papermaking machines to run at higher speeds, thereby increasing production rates. This drying method reduces energy use by one-third, reduces production costs by $5 per ton of paper, improves paper strength by 25%, increases productivity by as much as 80%, and reduces carbon dioxide emissions as well.

Multiport Cylinder Drying: The evaporative drying in a paper mill is accomplished by winding the continuous sheet of paper serpentine over a series of rollers. The rollers are pressurized with steam which condenses on the inside of the roller. The multiport cylinder drying concept uses an alternative method to remove the condensate from the drier, which reduces the condensate film thickness inside the drier to 25-30% of conventional technology. This improves heat transfer and increases drying.

On-Machine Sensors for Paper Properties: The development of new sensors to provide real-time feedback on whether the process and product are within specification can save the energy of reprocessing off-grade material and allow the use of greater amounts of recycled fiber. With an on-line sensor for strength properties the process variability can be reduced and greater proportions of recycled fiber utilized. A 10% reduction in refiner energy at a single mill saves more than 70 billion Btu/year. Reducing the normal off-grade production rate by 50% (from a typical 5% to 2.5%) can save an additional 118 billion Btu/year. If 300 plants adopted these sensors, the annual savings would be about 60 trillion Btu.

Biomass Gasification Cogeneration: The pulp and paper industry is about 57% energy self-sufficient, due to the use of wood residues (i.e., hog fuel and bark, pulping wastes, and cogenerated electricity). The gasification of biomass and electricity generation through a combined cycle would increase the electricity output of the paper industry, further reducing purchased electricity needs. To meet the in-plant process steam requirements, this biomass-based integrated gasification and combined cycle (BM-IGCC), would require an increased utilization of wood residues (about double) possibly from wastes in plantation forestry or other sources. If one-third of the current population of hog and bark boilers were to be replaced with BM-IGCC, many of which will be retired by 2010, then cogeneration output from the paper industry would increase by 17 billion kWh, about 27% compared to 1994 levels. This would reduce total U.S. industrial electricity purchases by 1.3% in 2010 and carbon emissions by about 1.3 million metric tons.

4.4.3 Chemicals

The chemical industry is almost too complex to characterize as a single industry. Some products – chlorine and other industrial gases – are made electrolytically or using electricity to compress and liquefy gases. Other processes, such as petrochemical processing, require high temperatures and pressures to effect the chemical combination or separation that is required. Within chemical manufacturing there are over 30 industries and more than 10,000 products. A recent study by Steinmeyer (1997) found that, in the chemicals industry, simple capital-energy tradeoffs (e.g., using larger pipes and heat exchangers) result in a 37% reduction in process energy consumption for a cost of less than 1.5% of total production costs; this study examined only energy-related costs. Another recent study by Elliot (1997) showed that productivity savings are often far larger than energy savings. For example, at the Louisiana Division of Dow Chemicals from 1982 to 1993, the average total annual savings from efficiency projects was 3.2 times the energy savings (Nelson 1993).

Reaction and separation are at the heart of most chemical engineering processes, and they typically require heat, high pressure, or both. Because of these requirements, the industry in 1994 used 5.3 quads of energy (second only to Petroleum Refining) and required nearly 16,000 Btu per dollar of product shipped. Promising technologies for the near-term are those that economize on the use of heat or cooling or bring the two in better balance. Examples are:

Pinch Analytical Techniques: The “pinch” technique was originally a method for optimizing heat recovery in thermal processes and has more recently been applied as a general optimization tool. Energy savings occur because of the heat recovery process (waste heat from one process is used to provide needed heat to another). In the classic case of heat exchanger networks, the pinch point helps to define the best match between available and needed heat, allowing the heat exchange system to be optimally sized for greatest cost-effectiveness. In early applications, energy savings averaged 30%, with capital cost savings in new plant designs, and one year paybacks in retrofits are common. Refinements to the technique have resulted in typical savings of 50% in new plants and retrofit paybacks of six months. By the mid-1980s the use of pinch analysis was widespread in the chemical industry, and its use has broadened further since then (WEC 1995).

Advanced Distillation Control Techniques: Distillation in refining and chemical industries consumes 3% of total U.S. energy use, which amounts to approximately 2.4 quads of energy annually. In addition, distillation columns usually determine the quality of final products and many times determine the maximum production rates. Distillation columns commonly use 30% to 50% more energy than is necessary to meet the product specifications. It has been estimated that an overall average 15% reduction of distillation energy consumption can be attained if better column controls are applied.

4.4.4 Petroleum Refining

The most energy-intensive processes are: distillation; catalytic hydrocracking, reforming and hydrotreating; alkylation; and hydrogen production. Efficiency improvements can be achieved in the following ways: (1) introduction of more efficient equipment; (2) reducing process activation energies (through improved catalysts); (3) improving equipment integration to recover more heat; and/or (4) adopting improved process control.

4.4.4.1 Monitoring Overall Energy Performance

Refineries could promote energy efficiency by rigorously pursuing a program to monitor equipment/process/overall refinery energy performance to identify when a system or piece of equipment begins to become inefficient so that corrective actions can be initiated.

4.4.4.2 Utility System Improvements

The principal utility systems in a refinery are the cooling, steam power, and fuel-gas systems; they are integrated with virtually every process subsystem. While their impact on the overall refinery operating profit margin is relatively small, the potential for energy savings is substantial (see appendix for details).

4.4.4.3 Process/Equipment Modifications

Major opportunities to reduce energy usage also exist through retrofitting and/or replacement of existing equipment nearing the end of its useful life. Examples of such opportunities are as follows:

<u>Fired (Process) Heaters.</u> Over 60% of the energy used in refineries is obtained from burning gaseous fuels in refinery heaters. For higher temperature processes such as steam reforming, the application of advanced oxy-fuel combustion systems such as Dilute Oxygen Combustion can result in net fuel savings of 25%. These gains can be enhanced further by converting natural gas to hydrogen and carbon monoxide, making use of waste heat generated by the Dilute Oxygen Combustion System.

<u>Boilers.</u> About 20% of all energy used by petroleum refiners is used for generation of steam. One route for improving boiler efficiency is through improved sensors and controls. For example, balancing the burners in a multi-burner boiler and reducing excess air can cut fuel use by 10 to 25%. In single-burner boilers, controlling

excess air can lead to similar gains. The technology to automate excess air firing is available, but a practical system remains several years away.

4.4.4.4 Fluid Catalytic Cracking

Fluid catalytic cracking (FCC) is currently the most energy-efficient and widely used of the cracking processes. Improved computer simulations of cracking kinetics should result in an improved commercial technology by the year 2008. Introduction of improved catalysts and other process modifications would occur somewhat later. FCC improvements could eventually lead to CO_2 reductions of up to 8 MtC.

4.4.4.5 Fouling Mitigation in Heat Exchangers

Seven percent of the total energy consumed in petroleum refining is due to extra energy needed to run heat exchangers that have a fouling build-up. Research indicates that improved operations and retrofits can reduce fouling. An accelerated program of heat exchanger retrofits and better understanding of fouling conditions could reduce CO_2 emissions by 0.5 MtC by 2010.

4.4.5 Glass

The glass industry is comprised of several major product segments, each with their own processes for producing final products. The segments include container, flat glass, wool and textile fiber, specialty, lighting, and hand glass. The major common energy-intensive stage of the glass industry is the glass furnace. There are nearly 500 furnaces in over 200 plants in the glass industry (ignoring the smaller hand glass segment). While there are other stages of product finishing which also require significant amounts of energy, the examples below focus on the glass furnace as the primary area of concern for energy efficiency. Other process and product specific areas of energy efficiency are also possible.

4.4.5.1 Oxy-Fuel Process

Since 1991, the fiber, container, and specialty glass industries have accepted the oxy-fuel process as an alternative to regenerative and recuperative air-fuel furnaces. According to one source, more than 50 major furnaces (20 ton/day) have been converted to oxy-fuel combustion technology (Geiger 1996). In the oxy-fuel process, oxygen or oxygen-enriched air is used in combustion in the melting furnace. It is reported that fuel savings from oxy-fuel conversions are typically 10-15% for well designed soda-lime regenerative furnaces, and at least 30-40% for direct fired or regenerative boro-silicate or lead glasses (Ross 1996). Currently, approximately 15% of the large commercial furnaces in the U.S. have been converted to the oxy-fuel process (Ross 1996).

Oxy-fuel technology also increases furnace productivity by 25%, reduces defects, and eliminates the need for heat recovery (DOE/OIT Impacts, December 1996). There is also a waste-heat-driven thermal swing absorption (TSA) process for producing low-cost oxygen for this process. The TSA system can be used in both the glass and steel industries. This low-cost absorption system selectively absorbs oxygen from air at a cost 30% lower than the best conventional system. This new technology increases productivity dramatically, reduces fuel use by 60%, nitrogen oxides (NO_x) emissions by 50%, and particulate emissions by 30%. The system also eliminates the need for other more costly add-on NO_x and particulate control equipment to meet increasingly stringent environmental regulations for glass and metal melting. The expected energy savings are 28 trillion Btus ($70 million) annually.

4.4.5.2 Advanced Burner Technology

Adoption of newly developed burners in the oxy-fuel process further improves the energy efficiency of the process. Some recent burner designs have shown as much as a 30% decrease in fuel use, as well as improvement of product quality.

4.4.5.3 Glass Batch/Cullet Preheater Technology

The dual batch/cullet preheater uses the oxy-gas furnace's waste heat to preheat cullet and batch before feeding it to the furnace. Preheating cullet and batch reduces the amount of energy and oxygen required in the overall melting process (*GRID* 1996).

4.4.6 Aluminum

Aluminum smelting is highly capital-intensive, with capacity cost estimates ranging from $3,000 per metric ton for expansion of existing facilities to $5,000 per metric ton for new facilities (DOI 1993). Low energy costs in countries such as Brazil, Canada, and Australia have made the international aluminum industry extremely competitive, and near-term construction of smelting capacity is not expected in the United States. Investment in state-of-the-art technology has also been limited by capital constraints. A variety of technologies exist, however, that have the potential to incrementally reduce energy intensity in the aluminum industry in the time frame to 2010.

4.4.6.1 Improving Hall-Heroult Cell Efficiency

The current U.S. composite baseline energy intensity for aluminum smelting is estimated at 15.2 kWh/kg of aluminum, with the potential near-term reduction using retrofit technology estimated at 13 kWh/kg (Energetics 1997). Performance in the range of 13 to 15 kWh/kg has been achieved in domestic smelters through a variety of techniques including enhanced potline controls, better anode rod connections, improved cathode block materials, and increases in anode size resulting in lower current density (Newsted et al. 1992, Jeltsch and Franklin 1992). Additional research to design dimensionally stable cells and to optimize materials use for internal control of cells, and to use signal analysis to analyze cell voltages in potlines, are seen as areas which can improve smelting performance in the next ten years (Energetics 1997). The primary barriers to adoption of high-efficiency technologies may be economic.

4.4.6.2 Materials Recycling

Remelting aluminum scrap requires only a small fraction of the energy required to smelt aluminum from alumina. Remelting is also far less capital-intensive than smelting, which reduces barriers to modernizing. In 1995, aluminum recovered from old scrap was equivalent to about 35% of apparent consumption in the U.S. (DOI 1994). While some of the barriers to higher recycling rates are institutional (e.g., perceived value of recycling beverage containers), technological barriers also exist for some products like aluminum in cars. These include problems with scrap sorting, separation, cleaning, and pre-treatment, which inhibit the increased use of different types of scrap and also contribute to problems with metal quality. Byproduct recycling (e.g., salt cake and spent potlining) is also inhibited by a lack of knowledge of byproduct characteristics. A critical review of the U.S. recycling industry infrastructure could identify ways to enhance aluminum recycling rates (Energetics 1997). Given the magnitude of energy savings associated with recycled aluminum versus virgin aluminum, enhanced recycling may offer the greatest energy savings and greenhouse gas emissions reduction opportunities in the short term.

4.4.6.3 Improve Furnace Efficiency

Improving energy efficiency of melting and holding furnaces offers potential for energy savings in the secondary aluminum industry. Several commercially available technologies exist for reducing energy use in furnaces, including heat recuperators and regenerators and the use of oxygen-assisted combustion. Heat recuperators operate by passing the combustion products through heat exchanger tubes, thus allowing the preheating of inlet combustion air and recovery of heat that would otherwise be exhausted to the atmosphere. Heat regenerators accomplish heat recovery through a paired burner/exhaust system in which the burners alternate in the firing mode in cycles lasting about 20 seconds. Oxygen-assisted combustion uses oxygen in a dual-firing burner to increase furnace melt rates, reduce energy use, and reduce emissions. Energy savings from oxygen-assisted combustion can be substantial (Heffron et al. 1993).

4.4.7 Iron and Steel

Iron and steel industry comprises the ore-based integrated steel plants, the dominantly scrap-based “mini-mills,” and specialty steel mills. Steel production via integrated plants has been decreasing, while that of the electric arc furnace (EAF) based mini-mills has been increasing. At present, the production capacity of the mini-mills is comparable to some of the smaller integrated plants. Mini-mills are more energy-efficient, since they use scrap or directly-reduced iron or hot-briquetted iron. If the mini-mill relies mainly on scrap, the range of products that can be produced is somewhat limited by scrap quality issues.

4.4.7.1 Direct Smelting / Direct Reduction

The ongoing process development activities in iron making in the U.S. and abroad clearly indicate a need to minimize coke consumption and increase the use of natural gas and/or coal as a reductant for making solid and/or liquid iron. Energy savings from such technologies arise from by-passing the coke-making stage and frequently from very high throughput. For example, Kobe Steel and Midrex Direct Reduction Corp. have developed a production approach for molten iron that reduces the process from hours to minutes (Metals Industry 1996). Because the product is in molten form, there are savings in downstream steel making operations and the material can be cooled to iron shot or ingots without reoxidation.

This technology eliminates the production of coke and reduces the need for ore preparation by integrating three steel processes into one. Coke-making and ore preparation are responsible for the largest portion of emissions in primary steelmaking. This technology reduces energy consumption by 20-30% and capital costs by 25-50% compared to conventional blast furnace technology. The first commercial applications of this technology are operating in Europe.

4.4.7.2 Scrap Preheating

Energy consumption in EAF operations can be reduced by preheating scrap to approximately 400°C with EAF offgases. Heated metal charges comprising 20-30% of inputs can result in power consumption rates of less than 300 kWh/tonne of liquid steel (Scheidig 1995). The potential energy savings is roughly 90 kWh/ton of liquid steel. For a DC Fuchs shaft furnace, compared to a conventional DC furnace, energy savings of 13.5% and reduced electrode consumption of 29% are estimated. Baghouse dust reduction is estimated at 30% (Haissig 1994). In the dual shaft furnace design, iron particles in the offgas tend to adhere to the scrap, resulting in iron recovery in the melt and leaving the offgas zinc-enriched (Burgmann and Pelts 1995). If zinc levels are enriched to above 25%, the dust may be an acceptable input to zinc refining, rather than requiring disposal as a RCRA-listed hazardous waste (Center for Metals Production 1987). Preheating also reduces furnace tap-to-tap time (normally about an hour) by 12 to 15 minutes (Scheidig 1995), resulting in increased raw steel production capacity, measured in terms of sustainable annual production.

4.4.7.3 Hot Connection

Depending on plant layout, moving forms from the continuous casting operation to the rolling operation with minimal cooling may provide energy savings. Reheat furnaces are generally employed to bring the cast forms back to rolling temperature. Adjusting plant layout to move the cast semi to the rolling operation at a temperature of 600° to 800°C can result in an energy savings of 0.4 to 0.6 GJ/tonne of semi based on the IISI reference plant defined in 1982 (Etienne and Irving 1985). A Dutch study based on a transport or connection temperature of 700°C estimated an 18% reduction in energy for reheating, for a savings of 0.3 GJ/tonne of crude steel (De Beer et al. 1994).

4.4.7.4 Near Net Shape Casting

Near net shape casting provides an example of an innovative and energy-efficient technology that has experienced rapid penetration in a capital- and energy-intensive industry. It is the direct casting of the metal into (or near to) the final shape (e.g., strips or sections), replacing the present energy- and capital-intensive processes of continuous slab casting, slab reheating, and hot rolling. Near net shape casting uses 25% less energy than the current best practice conventional technology. The first commercial application, thin slab casting, was introduced in 1989 and now accounts for one-quarter of all U.S. thin slab production capacity. Using this technique, sheet steel can be produced at a cost of $250/ton compared to conventional technology costs of $350/ton.

4.4.8 Metal Casting

Metal casting is not a single industry segment according to the SIC system, but covers a diverse group of products and metals. Products range from cast pipes, motor vehicle components, and tools. Iron, steel, aluminum, copper and zinc are all metals used by the industry. The industry is labor intensive, with many small plants; four out of five have fewer than 100 workers. Over half of the energy use is in melting metal. Technologies which improve the melting stage or reduce waste/recasting have important energy implications.

4.4.8.1 Computer-Aided Casting Design

Rapid advances in computer modeling of the casting process and in computer-aided drafting of castings have led to an increased use of computers in foundries, and hence, an increased need for integration in casting design systems. Increased integration in the casting design functions is needed to realize the full potential for improving both casting designs and production lead time. Two kinds of information are produced by the casting analysis and simulation function: (a) predicted outcome of casting the current design; and (b) the processing parameters for the casting process, if the casting design appears sound. The predictive results allow the foundry engineer to evaluate the filling of the mold cavity, the potential for defects such as porosity in the casting to occur, the sequence of solidification, and the time for complete solidification. With computer modeling, an average of 25% improvement was found in casting yield (Lensen 1996, Lensen et al. 1995), which would comparably reduce energy use for metal remelting.

4.4.8.2 Optimized Coreless Induction Melting

Most foundries can dramatically reduce a major portion of their energy through optimization of their induction melting equipment. It has been estimated that foundries are only operating their induction furnaces at 50-80% of their optimal efficiency (Horwath et al. 1996). A foundry melting 1000 tons/month could reduce its monthly melting costs by $5/ton by installing sensors and computer optimization of its melting practice. Four major variables are important in determining the power required for melting: (1) charge makeup, (2) furnace cover, (3) power application, and (4) furnace condition. In some cases, optimal material use resulted in higher energy use (22% more). Use of a furnace cover reduced energy consumption by 12%. Furnace condition (i.e., hot, medium, or cold) interacts with the charge to significantly affect energy consumption. Maintaining the furnace in hot condition resulted in 15.4% less energy consumption for melting the charge (Horwath et al. 1996).

4.5 THE LONGER TERM: FUTURE TECHNOLOGIES AND R&D POTENTIAL

The technologies cited above are currently available, or soon will be, because of past R&D. For future technologies to contribute to increased energy and emissions reductions presumes a continued stream of R&D activities into the future. Recent efforts by the Department of Energy are directed at ensuring that steady stream of R&D by partnering with industry.

The Office of Industrial Technologies, in an effort to garner support and make their research and development activities more in line with the needs of industry, has initiated a joint government-industry planning process called the "Industries of the Future." The vision of the way that future industry will function and the technologies that the industry will use shapes, in part, the organization and implementation of government R&D efforts. It is this process that may lead to an invigorated effort to develop future technologies that will improve energy efficiency and reduce carbon emissions.

In this section we discuss the potential for additional decreases in energy intensity in the future as a result of the continuation of future R&D efforts. Here we draw heavily on the vision documents that have been published or are being prepared by the energy-intensive industries under the OIT's Industries of the Future process. We discuss general areas of potential advancement or provide specific examples of some of the technologies or technology areas that show particular promise for reducing energy consumption and concomitant greenhouse gas emissions.

4.5.1 Pulp and Paper

The Vision process for the Forest Products Industry of the Future was developed by the industry in collaboration with the Department of Energy's Office of Industrial Technologies, and is called “Agenda 2020 – A Technology Vision and Research Agenda for America's Forest, Wood, and Paper Industry.” Two of the major concerns of this document are Environmental Performance and Energy Performance. One way these objectives might be met is through the use of polyoxometalate bleaching.

4.5.1.1 Polyoxometalate Bleaching

Traditionally, the last remnants of lignin from the pulp have been removed with a chlorine bleaching process. However, the environmental impacts of chlorine have lead to significant efforts to find alternative methods to produce a desirable soft white fiber. Among these have been ozone bleaching and peroxide bleaching. Unfortunately, nothing has come to market which is as effective and selective as chlorine or chlorine dioxide. Polyoxometalates may be just such a new process. They are highly selective and can be regenerated within the process. In addition to desirable performance characteristics, the polyoxometalate system is consistent with the goals of increasing recycling of process water and reducing the effluent load from pulp mills. Compared to chlorine based systems, the new process promises to reduce electrical energy consumption of pulp bleaching by 50%.

4.5.2 Chemicals

4.5.2.1 Biological/Chemical Caprolactam Process

Nylon-6 is currently produced from caprolactam. The chemical synthesis of caprolactam from cumene is a complex, multi-step process that is energy-intensive and generates considerable waste. Nylon-6 could also be produced from caprolactone. However, the current market price for caprolactone makes this route uneconomical.

A laboratory-demonstrated biological process has been developed that would provide a one-step, cost-effective production process for caprolactam manufacture that requires 50% less energy than the current process, costs half as much (considering both capital and energy costs), and produces almost no waste byproducts. Research on this process has established the technical feasibility of the biomanufacturing process for converting inexpensive cyclohexane into caprolactone. Under this project, the feasibility of the laboratory-demonstrated biomanufacturing process was established, and the process is now available to be optimized for possible scale-up to pilot plant scale. It is estimated that, by the year 2020, this technology can provide annual energy savings of 12 trillion Btu (DOE 1997). While this is a modest total savings (the chemical industry used over five quads in 1991), this is just one of tens of thousands of chemical processes.

4.5.2.2 Flexible Chemical Processing of Polymeric Materials

Waste textiles and recycled waste materials from automobiles, appliances, and furniture contain polymers (such as nylon-6, nylon-66, PET, and polyurethanes) that can be converted into valuable chemical feed stocks. However, processes that can only convert a single type of recycled material can face high costs for material collection and for transportation of the resulting feed stocks. Because these costs are the major contributors to process costs, processes are needed that can convert a variety of recycled materials.

Research in this area is working toward developing a thermochemical process that can convert a wide variety of recycled materials into valuable chemicals. A two-stage process is envisioned: the first will use selective catalytic pyrolysis to recover chemicals such as caprolactam, hexamethylendiamine, and dimethyl-terephathalate; the second will convert the unreacted organic material into synthesis gas, which can be converted to a variety of chemicals of use to the chemical industry.

Because the process can address a wide variety of recycled materials, large regional recycling plants can be developed, lowering material collection and transportation costs, and thereby increasing the viability of recycling many materials. It is estimated that, by the year 2020, the use of this technology will save 265 trillion Btu annually (DOE 1997).

4.5.2.3 Genetic Engineering

Many chemicals firms are investing heavily in genetic engineering and, over the next decade, many expect to commercialize products. Low-carbon biotechnologies include engineered plant systems to allow crops to fix their own nitrogen from the air (thus avoiding N_20 emissions associated with fertilizer manufacture); agricultural “petroleum plants” that grow feed stocks for the chemicals industry; and intermediate products such as polymers.

4.5.3 Petroleum Refining

The National Petroleum Council issued a report in 1995, “Research, Development, and Demonstration Needs on the Oil and Gas Industry”, which identifies the future of the industry in 2020. It stresses, among other things, the need for flexibility in processes as well as new chemistries and materials. Changing input feed stocks and environmental requirements will tend to push the industry toward higher energy use in 2020, without developments such as new catalysts or other process changes that are on the horizon.

4.5.3.1 Development of Improved Catalysts

The purpose of a catalyst is not to lower the energy needs of a reaction (which are governed by thermodynamics) but to lower the energy required to activate a process and thereby increase the kinetics and/or product selectivity. If it accomplishes either or both of these tasks, the energy demands on a given process should decrease either due to lower heat demand (lower energy of activation) or from greater throughput. Most of the energy use in a refinery that could benefit from improvements in catalyst technology is consumed in one of three major process areas: (1) hydroprocessing, (2) catalytic cracking, and (3) alkylation.

In hydroprocessing, much energy is utilized in heating up heavy oils and resids to temperatures at which the catalyst activity is high enough. Additional energy is expended in the compression of hydrogen to pressures up to 2000 psi. Improved catalysts (capable of functioning at lower temperatures and pressures) could reduce the energy used by decreasing the reaction temperature of this process.

Energy usage could be improved for catalytic cracking in terms of product selectivity. Cracking catalysts are extremely efficient at converting "good" gas oils to gasoline and distillate. However, when significant fractions of resid and the metals that accompany these resids are used as fluid catalytic cracking (FCC) feeds, the selectivity (in terms of gasoline yield) drops precipitously. This gasoline loss comes at the expense of increased coke and dry gas production, which in turn requires catalyst coolers in order to keep the temperature of the catalyst bed down (required by increased coke burn) and higher compressor capacity to handle the increased dry gas yield. If catalysts were designed to handle higher amounts of heavy oils without the detrimental effects outlined above, then more resid could be handled in the highly efficient FCC with resulting decreased utilization of the less efficient hydrotreaters.

The largest energy demand in the alkylation units are in the refrigeration units used to keep the hydrofluoric acid temperature down. Here the need is for a catalyst which will operate at temperature above ambient. Many solid alkylation catalysts which are in pre-commercial testing and evaluation function at temperatures around 150°C. Many of the streams requiring alkylation are at or near this temperature when they exit their respective processing units. Such heat is normally considered waste heat and thus could easily be utilized for the alkylation process. Therefore, even though the reaction temperature would go up, the energy demand would decrease.

4.5.4 Glass

The glass industry vision of itself in 2020 is defined in “Glass: A Clear Vision for a Bright Future”. This vision document includes, as one of many goals, reducing process energy use from present levels to 50% toward the theoretical limit of 2.2 million Btu required to melt a ton of glass. On April 29, 1996 a compact between the DOE and the major glass producing companies was signed to enable collaboration in such areas as waste reduction, energy efficiency, and quality control. The technology road map is currently under preparation. The technologies below are just a few examples of areas of glass industry technology development.

4.5.4.1 Optimizing Electric Boost to Reduce Total Energy Consumption

High energy efficiency, through conversion of electric energy into useful heat, and low volatilization are the primary advantages of electric melting. Current operating practice has shown that effective use of electricity near the back end of the furnace, where the batch is added, can reduce fossil fuel needs. Research needs for optimizing electric boost include, but are not limited to, investigating new electrode and electric arc melting processes, modeling of the current technology to fine-tune operation conditions, such as energy inputs and locations of the electrodes, and improving the electrode control system (Glass Industry Working Group).

4.5.4.2 Recovering and Reusing Waste Heat from Oxy-Fired Furnaces

Recovery and reuse of waste heat from the oxy-fuel process will further increase energy efficiency of the process. Preheating the batch and cullet, described above, is one method to recover heat from the flue gas. Other options, such as regenerative oxygen heat recovery (Browning and Nabors 1996) and a "synthetic air" concept (Argent 1997), have been proposed and need to be tested and evaluated. A Thermal Swing Adsorption (TSA) oxygen production process has been demonstrated in the laboratory with enrichments of up to 89%. The process is based on synthetic chemicals that can reversibly bind oxygen at low temperatures and release it at elevated temperatures. The operation is in a temperature range of 70° to 220°F, so low grade waste heat can be used to drive the process, and the external energy required for produce oxygen can be reduced.

4.5.5 Iron and Steel

"Steel – A National Resource for the Future" broadly defines four areas of R&D to shape the industry in 2020. These include production efficiency (which encompasses energy efficiency), recycling, environmental engineering, and product development. The goal of increasing steel production to over 70% of recovered scrap would have major implications for energy use. DOE and the two major steel industry trade groups have signed a R&D collaborative compact to work together on the first three of the four research areas. Below, we discuss some of the process areas within which energy and other savings are likely to be achieved from technical breakthroughs.

Activity will be largely dictated by the viability of different iron making processes that are under development. R&D effort should focus on developing a process scheme that incorporates both iron making and steel making into one system with thin strip casting as a final product. The effort should incorporate a coal-based reductant process which can be coupled with steel making operations and simultaneously produce power in a combined cycle that includes both gas and steam turbines.

Steel making processes currently utilize computer technology, primarily to implement prespecified procedures in a timely manner. There is very little feedback in these systems to either enhance process efficiency or improve the product quality. Key process parameters should be identified so that interactive logic and high-speed computer systems can be used to control/modify/maintain these process parameters to obtain a quality product. Such an intelligent-processing approach is essential for the production of so called "cleaner steel" with low residual elements.

The development of sensors for all aspects of process control and for enabling process changes with a feedback system is essential for improving process efficiency and optimizing different stages of the melting, casting, thermomechanical processing, and final heat treatment. Applications of novel ideas and approaches need to be explored and transfer of technologies available from defense and chemical processing industries may be a fruitful approach.

4.5.6 Metal Casting

A diverse group of CEOs and presidents from the foundry, die casting, and foundry supply companies co-authored "Beyond 2000: A Vision for the American Metal Casting Industry." This vision of the industry identifies six critical areas: production efficiency; recycling; pollution prevention; application development; process controls; and new technology development. The specific goals include increasing productivity by 15% and reducing energy consumption by 3-5% by 2010. The Cast Metals Coalition is preparing a R&D strategy to achieve these and other goals identified in the industry vision. Some examples of technology areas are given below.

Electromagnetic Casting: An electromagnetic field in a casting is used to induce eddy currents in the liquid metal that, together with the field, stir and contain the liquid metal in the casting. Two examples are discussed below:

EM Stirring: In continuous casting, the solidification process can be improved by EM stirring, producing better metallurgical results, improved internal quality of the casting, and even reduced meniscus instability and surface defects (Beitelman and Mulcahy 1994, Chang et al. 1995). The benefit from EM stirring takes the form of reduced wastage per cast. As a minimum, we expect that the present average yield of 55% for the industry can be increased to 65%, a savings of 130,000 tons per year, with an associated energy savings of 25 trillion Btu per year (American Foundrymen's Society 1995).

EM Confinement: In the presently dominant sheet-forming process, thick steel slabs are cast and then hot-rolled. Twin-roll casting with EM confinement has the potential to cast thin sheets by eliminating the hot-rolling stage, giving the sheet product an enormous economic advantage over products made by competing methods (Saucedo and Blazek 1994, Blazek et al. 1994) and completely by-passing an energy-intensive stage of production.

4.6 CONCLUSIONS

This chapter presents an approach to assessing the potential for efficiency to reduce energy use in the most diverse sector of the economy, the industrial sector; this approach represents a compromise between the desire for technology detail and the need to evaluate sector-wide energy use. The approach uses two publicly available models, Argonne's Long-term Industrial Energy Forecasting (LIEF) model and the Energy Information Administration's industrial module from the National Energy Modeling System (NEMS), to simulate a plausibly optimistic set of scenarios for additional energy savings, relative to an established base case (AEO97). The models are used to project what energy savings could arise from an 'invigorated effort' to put currently available or near commercial technologies into practice in industry. This invigorated effort is loosely characterized by either a combination of new policy initiatives or a more serious consideration of efficiency as a strategic concern of industrial decision makers.

Two efficiency cases are presented in order to project overall reductions in energy use by 2010. A reduction of 5-10% is projected to be technically feasible, given adequate policies or other incentives to expand the adoption of cost-effective measures. This is about 2.5 quads in the high case. The LIEF model projects that these reductions could arise from cost-effective investments defined by a capital recovery factor of 15% (about a seven year pay-back). The LIEF model does not assume that in every case all energy-efficiency investments are made, but an increased penetration rate of efficiency investment is assumed relative to the base case as a result of this 'invigorated effort'. For many of the energy-intensive industrial sectors, these projected energy savings are consistent with roughly doubling the current rates of capital stock replacement or doubling the rate of energy technology efficiency improvement that is currently represented in the NEMS model.

Since the models used to conduct the scenario analysis do not have a detailed, technology-specific representation of each major industrial sector, the chapter also provides illustrative examples of technologies for most of the energy-intensive industries. These are examples of technologies that have the potential to reduce energy use relative to current practices if widely adopted. These technology examples exhibit substantial energy savings relative to current industry practice, so they reinforce the fact that the model results are feasible. But one cannot expect these technologies to be adopted widely unless there is some invigorated effort to encourage their adoption. The slow turnover of the capital stock in the energy and capital intensive industries is one reason that this invigorated effort would be needed. Under conservative projections, in the near-term, many of these technologies (and the many others not listed here) are capable of reaching high levels of penetration but most will not achieve 100% penetration. However, the examples show that there are many ways in which efficiency in industry can be increased, given the right incentives; the examples help establish the technical plausibility of the projections.

The efficiency case projections also show that, on a percentage basis, there are more savings in 'light' non-energy-intensive industry vs. the 'heavy', energy-intensive sectors. This result arises from the LIEF model scenarios but, due to the structure of the model, does not have an analog in NEMS. Because the share of total production costs attributable to energy use in the non-energy-intensive sectors is very low (the manufacturing average is about 3% and most light industry is less), it is not surprising that the range of energy performance is quite broad. Energy-efficient technologies, in the form of motor systems as well as lighting and HVAC options (similar to those discussed in the commercial section of Chapter 3), represent cost-effective investment opportunities in light manufacturing. However, there may not have been a managerial or technical focus on energy efficiency in those industries. An 'invigorated effort' could provide this focus. On the other hand, to reduce energy use in 'heavy' industry, where considerable attention to efficiency has already been paid, low capital turnover rates and difficulty in financing medium to large investments may be the major impediments to accelerated improvements in energy utilization. This 'invigorated effort' in these sectors might require tax incentives, alternative financing arrangements, new developments that lower first cost, or demonstration projects that lower perceived risk. The diversity among these broad categories of industry implies that the mix of policies required to achieve the high-efficiency case may differ for the various types of industries, based on their current business and technical practices as well as current domestic and international market conditions.

For all of the industries discussed above, further progress in energy efficiency beyond 2010 requires further developments in technology. These developments may be *incremental* improvements (e.g., sensors, controls, and system/process modeling) or may be *fundamental* breakthroughs (e.g., catalysts, direct smelting, or bioprocessing). Incremental improvements need not be associated with ‘small’ efficiency changes. The ability to sense and adjust a process to achieve optimal operating conditions can have large effects on productivity and energy consumption. However, the search for totally new methods to produce a product with fundamental breakthroughs in chemistry, metallurgy, or biology offers another route to enhance productivity and lower energy use. These two avenues of R&D to create the manufacturing sector of 2020 are both being sought by private and private/public partnerships.

Table 4.15 summarizes the technology examples presented above. A rough categorization of incremental (I) and fundamental (F) has been made. Many of the underlying concepts in the examples apply to other sectors, while others are very process specific. This identification is made as well. In should be noted that the year 2010 designates current (on very near commercial) technologies, while the year 2020 designates technologies that will require further R&D, with no prediction of a commercialization date.

The range and types of technological solutions in industrial applications is quite large. Since energy represents a cost, and energy efficiency a potential source of profit, these technical solutions can fit within the economic goals of business. With the right incentives, higher energy efficiency of the magnitude projected here in the industrial sector is an achievable goal.

Table 4.15 Summary of Technology Examples

			Type of		
Aluminum	Improve Furnace Efficiency	2010	I	Y	EF
Aluminum	Materials Recycling	2010	I	Y	E
Aluminum	Improving Hall-Heroult Cell Efficiency	2010	I	N	E
Aluminum	Wettable Cathodes	2010*	I	N	E
Aluminum	Inert Anodes	2010*	I	N	E
Chemicals	Pinch Analytical Techniques	2010	I	Y	F
Chemicals	Advanced Distillation Control Techniques	2010	I	N	F
Chemicals	Flexible Chemical Processing Of Polymers	2020	F	N	F
Chemicals	Biological/Chemical Caprolactam Process	2020	F	N	F
Cross-cutting	Combined Heat and Power	2010	I	Y	EF
Cross-cutting	Motor Systems	2010	I	Y	E
Glass	Glass Batch/Cullet Preheater Technology	2010	I	Y	F
Glass	Advanced Burner Technology	2010	I	Y	F
Glass	Oxy-Fuel Process	2010	I	N	F
Glass	Producing Oxygen More Efficiently	2020	I	Y	E
Glass	Recovering Waste Heat	2020	I	Y	F
Glass	Maximize Combustion Efficiency	2020	I	Y	F
Glass	Optimizing Electric Boost	2020	I	N	F
Iron and Steel	Process Controls	2010	I	Y	EF
Iron and Steel	Hot Connection	2010	I	Y	F
Iron and Steel	Scrap Preheating	2010	I	Y	EF
Iron and Steel	Use Of DC, Rather Than AC, EAFs	2010	I	N	E
Iron and Steel	Coal Or Natural Gas Injection	2010	F	N	F
Iron and Steel	Direct Smelting /Reduction	2010	F	N	F
Iron and Steel	Process Controls And Sensors	2020	I	Y	EF
Iron and Steel	Direct Smelting & Thin Strip Casting	2020	F	N	EF
Metal Casting	Computer-Aided Casting Design	2010	I	Y	EF
Metal Casting	Optimized Coreless Induction Melting	2010	I	N	E
Metal Casting	Electromagnetic Stirring	2020	I	N	EF
Metal Casting	Electromagnetic Casting	2020	F	N	EF
Petroleum Refining	Utility System Improvements	2010	I	Y	F
Petroleum Refining	Process/Equipment Modifications	2010	I	N	F
Petroleum Refining	Development Of Improved Catalysts	2020	F	Y	F
Pulp and Paper	On-Machine Sensors For Paper Properties	2010	I	Y	F
Pulp and Paper	Multiport Cylinder Drying	2010	I	N	F
Pulp and Paper	Impulse Drying	2010	I	N	F
Pulp and Paper	Biomass Gasification	2010*	I	Y	EF
Pulp and Paper	Black Liquor Gasification	2010*	I	N	EF
Pulp and Paper	Sulfur Free Pulping	2020	F	N	EF
Pulp and Paper	Polyoxometalate Bleaching	2020	F	N	EF

* Based on the accelerated deployment described in Section 4.3.

4.7 REFERENCES

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ENDNOTES

[1] Because they become very important in a low-carbon scenario, we have made an exception to this approach in the case of low-carbon technologies which are examined from the bottom-up. Unlike energy-efficiency technologies, there is no established modeling procedure or analysis method for assessing the penetration of low-carbon (especially low process carbon) technologies. Thus, we simply provide case studies and take their results as a lower bound on the potential.

[2] Differences in the industry subsector detail prevented us from doing a precise calibration of the two models. It is not clear that such a calibration would substantially improve our analysis for these purposes.

[3] Technologies that supplement the existing process (e.g., process controls) might penetrate rapidly, but most that are replacements for existing process will more likely follow the ‘normal’ turnover patterns. Technologies achieving rapid penetration include sensors and process control software and technologies that can save significant amounts of energy.

[4] The forest products industry includes pulp and paper, as well as lumber and wood products. This report focuses on the relatively more energy-intensive pulp and paper segment of the forest product industry.

[5] In particular, we do not change the underlying forecast for activity in the refining sector.

[6] The HE/LC case also includes low-carbon technologies described in Section 4.4. These low-carbon technologies are not explicitly captured in the computer model runs.

[7] Not all energy-intensive industries are “heavy.” The metal casting industry, for example, consists of many small shops owned by small businesses. It is important to distinguish OIT’s Industries of the Future and the “heavy industry” of Table 4.1. These “heavy” industries include non-vision industries such as food (SIC 20), non-refining petroleum (SIC 295, 299), stone, clay and cement (SIC 324-329), non-aluminum non-ferrous (SIC 3331, 3339, 3351, 3356, 3357, 3364, 3366, 3369). Conversely, the vision industries include wood and lumber (SIC 24), miscellaneous paper (SIC 265, 267), and miscellaneous chemicals (SIC 283, 285, 2879, 289), which are not included in the “heavy” industry of Table 4.1.

[8] These numbers are calculated from the numbers in Appendix A for Figure 16 in DOE (1995).

[9] Note that, in Figure 4.3, ATS in simple cycle power-only mode has a higher heat rate than the most efficient combined cycle turbine. However, even the power-only ATS emits far less CO_2 than the existing sources of power to the grid. In our calculation of the carbon reductions for ATS in power-only applications, we make the conservative assumption that the ATS has about the same emissions as new power plants. The carbon savings in this market come only from avoided T&D.

[10] As an average of 3 to 18 MW units (9 to 80 MW in multiple units), ATS are 43% efficient in simple cycle and can be 80 – 85% efficient (combined thermal and electric efficiency) when used for cogeneration (Hoffman, 1997).

[11] Constraints to growth of cogeneration have derived in part from the traditional requirement that steam and electricity loads be matched to maintain efficient and cost-effective operation of the cogenerator. The new ATS overcomes this problem by running efficiently at a wide range of electricity to thermal ratios. Cogeneration has also been constrained by environmental permitting, utility regulation, and utility competition. Together these factors explain why very efficient CHP technology still comprises a relatively small fraction of electricity and steam generation. When policies to promote CHP are instituted, however, this fraction can grow dramatically (Major 1995). Finland, Denmark, and the Netherlands have each achieved a contribution of about 30% of electricity production based on CHP.

[12] In the recuperator configuration hot exhaust gas from the turbine is used to preheat the air leaving the compressor prior to combusion, thereby reducing the amount of fuel required to reach the design turbine inlet temperature.

[13] See Appendix D-3 for details.

[14] Such reform would include standardized permits to reduce costs for small sites and a life cycle approach that takes into account power plant emissions and T&D for on site power permits.

[15] Current regulations, and some proposed utility deregulation legislation, include barriers to small on-site CHP. Both scenarios assume policies that elicit the cooperation of utilities in the increase in on-site generation. One scenario that could be imagined is that the utilities themselves finance and service these industrial ATS's for CHP and power generation.

[16] Carbon reductions from fuel switching were not included – a conservative assumption discussed in Apendix D-3.

[14]The calculations performed for both scenarios were reviewed by the American Forest and Paper Association and industry representatives (David Cooper and Delmar R. Raymond).

[18] The makeup of residual biomass and residue generation rates in various forest product and paper industries are described in Appendix D-5.

[19] Three large plants in the U.S. manufacture adipic acid and they are working with the EPA to reduce emissions (Boyd 1997). However, emissions from this process have increased by 9.9% since 1990.

[20] Many of the U.S. aluminum smelters are located in regions of the country with large hydropower resources, notably the Pacific Northwest (served by the Bonneville Power Administration), the Southeast (served by the Tennessee Valley Authority), and Northern New York. Under both scenarios, the aluminum smelters that would likely be converted first would be those in regions such as the Ohio River Valley that are dominated by coal-powered plants.

[21] 0.2 MtC = [(5 plants) * (190,000 tonnes of AL/plant)* (13,200 kWh/tonne of AL) * (89 gr of carbon per kWh) * 0.17]/1,000,000 grams/tonne.

[22] The carbon savings from the aluminum industry efficiency improvements that are already included in Section 4.2.2 must be subtracted in order to identify the increment that can be added by this analysis of alternative aluminum production cells. We calculate this as follows. Table 4.2 estimates that the aluminum industry as a whole will be 2% more efficient in its use of electricity in 2010 under the efficiency scenario, compared to the business-as-usual case. Under the assumption here that 5 of 22 smelters (23%) will be retrofitted with wettable cathodes that offer a 17% improvement in electricity efficiency, the nation's aluminum smelters as a whole would be 3.9% more efficient (3.9% = 0.23 * 17%). This represents a 1.9% efficiency improvement (or 0.09 MtC of emissions reductions) over the 2% that is assumed in the efficiency case in Section 4.2.2.

[23] 0.48 = (5 of 22 plants) * (50%) * 4.2 MtC.

[24] 1.0 MtC = [(10 plants) * (190,000 tonnes of AL/plant)* (13,200 kWh/tonne of AL) * (160 gr of carbon per kWh) * 0.25]/1,000,000 grams/tonne.

[25] The carbon savings from the aluminum industry efficiency improvements that are already included in Section 4.2.2 must be subtracted in order to identify the increment that can be added by this analysis of alternative production cells. We calculate this as follows. Table 4.2 estimates that the aluminum industry as a whole will be 3.8% more efficient in its use of electricity in 2010 under the high-efficiency/low-carbon scenario, compared to the business-as-usual case. Under the assumption here that 10 of 22 smelters (45%) will be retrofitted with inert anodes that offer a 25% improvement in electricity efficiency, the nation's aluminum smelters as a whole would be 11.4% more efficient (11.4% = 0.45 * 25%). This represents a 7.6% efficiency improvement (or 0.67 MtC of emissions reductions) over the 3.8% efficiency improvement that is assumed in Section 4.2.2.

[26] 0.6 MtC = (10 plants) * (190,000 tonnes of Al/plant) * (0.33 tonnes of C/tonne of AL).

[27] 1.91 MtC = (10 of 22 plants) * (100%) * 4.2 MtC.

[28] Note that almost none of the carbon savings due to Section 4.2.2's high-efficiency/low-carbon (HE/LC) case should be subtracted from this amount. The clinker replacement is not an efficiency increase, but a demand reduction. Thus, the drop in carbon emissions is nearly additive. We subtracted a very small amount because of the 8.1% reduction in cement industry energy use under the HE/LC scenario. The carbon savings due to a 5-20% reduction in demand is 2-4 MtC depending on the kiln technology. The amount we subtracted is about

5% of the total (0.06-0.08 MtC). If we assume that the penetration by 2010 is limited to the European owned firms (roughly half), then the carbon reduction is 1-2 MtC. Note that the HE/LC energy efficiency savings of Section 4.2.2 are equivalent to a carbon emissions reduction of just over 1 MtC depending on cement kiln technology.

[29] The Greenville Tube Company (GT) realized non-energy benefits ten times greater than the energy benefits when the company upgraded its motors. GT is a manufacturer of high-precision, small-diameter, stainless steel tubing. GT replaced an old motor and inefficient eddy current clutch drive with an energy-efficient motor with vector control. This new motor required fewer runs and produced far less scrap than the old system. The motor reduced annual energy consumption by 37% and resulted in savings of more than $77,000 annually from increased productivity, reduced scrap generation, and reduced energy costs.